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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Radiation Physics, contains six modules: Introduction to Radiation Laboratory Safety, Basic Radiation Detection and Measuring Equipment, Atomic Structure and Radioactivity, Radioactive Decay and Half-Life, Decay Processes and Schemes, and Basic Properties of Gamma Radiation. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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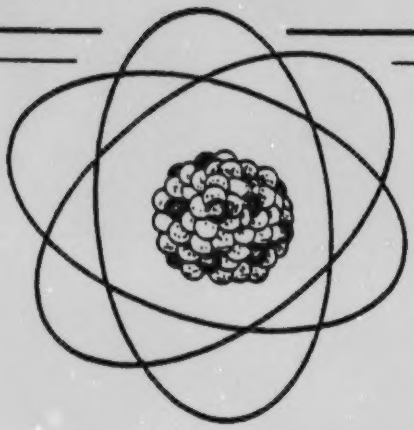
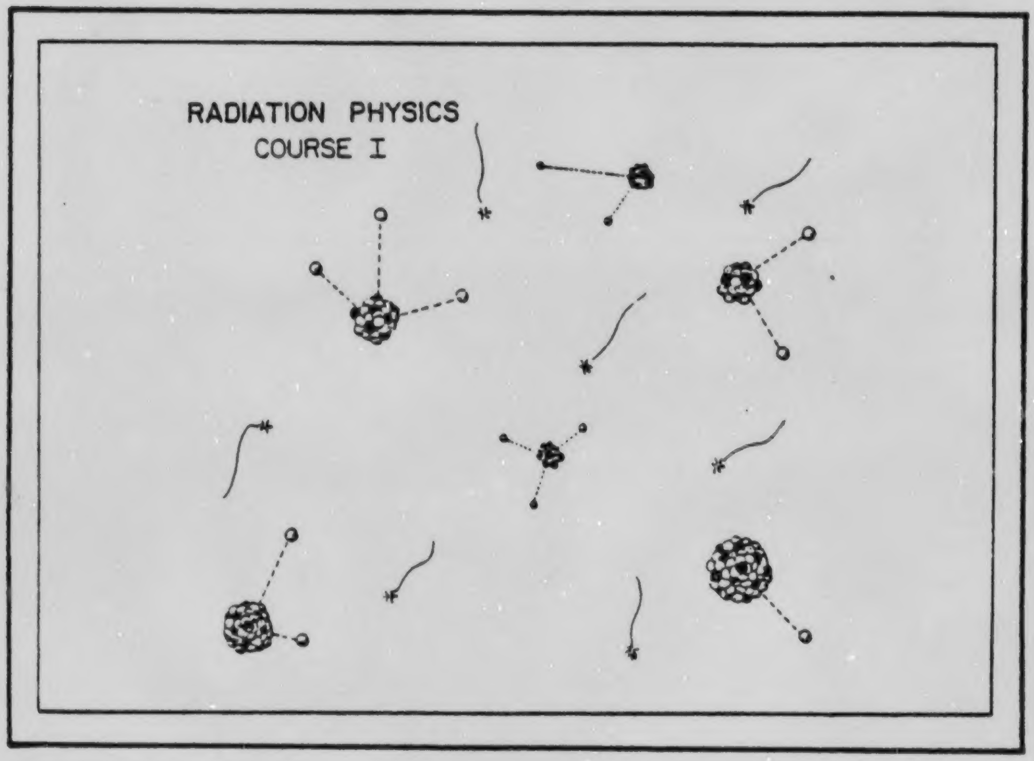


NUCLEAR TECHNOLOGY
Series

MODULE 1-1 INTRODUCTION TO RADIATION LABORATORY SAFETY



RADIATION PHYSICS
COURSE I

CE 026 644

U.S. DEPARTMENT OF HEALTH
EDUCATION & WELFARE
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COURSE MODULES

COURSE 1 RADIATION PHYSICS

⇨ MODULE 1-1	Introduction to Radiation Laboratory Safety
MODULE 1-2	Basic Radiation Detection and Measuring Equipment
MODULE 1-3	Atomic Structure and Radioactivity
MODULE 1-4	Radioactive Decay and Half-Life
MODULE 1-5	Decay Processes and Schemes
MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Radioactive materials enjoy many uses today in industry, medicine and agriculture, and in scientific research. The property that makes radioactive materials useful is their emission of energy in the form of electromagnetic radiation and very small particles. This release of energy is called radiation.

It is necessary to handle radioactive material with care because this radiation can adversely affect the health of laboratory personnel and the general public. In this respect, radiation is similar to other potential hazards such as electrical systems and corrosive or toxic chemicals.

By following a few important safety rules, laboratory personnel can be protected from adverse effects of radiation. The amounts of radiation necessary for most laboratory experiments are so small that health is not endangered even if an accident, such as a spill of radioactive materials, occurs. Even so, good laboratory procedures are to be practiced at all times, regardless of radiation levels involved.

In addition to adhering to radiation related safety rules, the normal safety principles and precautions involved in any physics, electronics or chemistry laboratory must be practiced in a radiation laboratory.

Finally, the most important safeguard to personnel is a sound knowledge and awareness of the hazards involved and good, common sense.

MODULE PREREQUISITES

None.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Briefly define the following terms:
    - Radiation.
    - Radioactive.
    - Monitoring.
    - Radioactive waste.
    - Decontamination.
2. List five principal characteristics of radiation.
3. State the primary objective of radiation safety for all personnel working in a radiation laboratory.
4. Describe in one paragraph each of the following items (in the context of a sound radiation safety program):
    - Careful monitoring.
    - Control of source strength.
    - Time of exposure.
    - Distance from source.
5. Draw the characteristic radiation hazard symbol and identify its appropriate colors.
6. State five principles for safely handling and containing radioactive material. Each principle must demonstrate a proper attitude toward radiation safety.

7. Describe proper disposal of laboratory radioactive wastes, both liquid and solid.
8. Identify each different type of radiation sign, label and tag. State the purpose and use.
9. Calculate the amount of radiation received during a laboratory period (from an initial and a final dosimeter reading).
10. Read and interpret from the "X1" range of a portable survey meter; discuss influence on radiation intensity as the distance to the source is varied and various absorbers are placed between the source and the meter.
11. Describe appropriate procedures for decontaminating radioactive materials spilled on the floor, including isolation, initial monitoring, protective clothing, absorbent materials, waste disposal and final monitoring.

WORKING WITH RADIOACTIVE MATERIALS

Some materials undergo nuclear disintegrations or transformations. These events are accompanied by the release of energy and one or more very small particles. These materials are said to be radioactive, and the energy and particles released are known as nuclear radiation. This nuclear radiation has many beneficial uses in industry, agriculture, medicine and scientific research. One such use is in the diagnosis and treatment of many diseases. Another use is to provide power for experiments on the moon such as was done during the Apollo moon mission. Further extensive discussion of uses of radioactive material will be given in following modules.

Most radiation discussed in this course is either alpha, beta, gamma or neutron. These types differ widely in their physical characteristics, penetrating power, response to radiation detection and measurement instruments, and degrees of health hazard. For example, alpha radiation is stopped by a single sheet of paper, but gamma radiation may penetrate several inches of lead.

Properties of these types of radiation are discussed in considerable detail in later modules of this and other TERC courses.

Some radioactive materials occur naturally, but most are artificially produced, either in nuclear reactors or particle accelerators. Some are produced by bombardment of the earth and its atmosphere by cosmic rays (as well as military nuclear explosions).

Radiation from radioactive materials has several important characteristics, including:

Insensateness - it cannot be seen, and its effects can be sensed only at extremely high exposure rates.

Spontaneousness - that is, no external stimulus is required for the radiation to be emitted.

Continuousness - it cannot be turned off. There is no known way to render radioactive material nonradioactive, except by natural decay.

Intenseness - radiation intensity decreases with distance from the source, similar to the decrease in sunlight intensity with distance from the sun.

Destructiveness - radiation in sufficient quantities can damage living biological cells. Note: The human body is able to tolerate reasonable amounts of radiation, as evidenced by (1) man's survival in spite of continued bombardment by cosmic rays, (2) properly administered medical and dental x-rays and (3) minute quantities of radioactive materials within the bodies and in the materials of everyday life.

Some people still mistakenly believe that all radiation is harmful and any radiation should be avoided at all costs. This belief generally stems from an ignorance of the basic facts about radiation. While there are still some differences of opinion, when properly trained persons use radiation, there is no reason to be more concerned with the radiation hazard than with other safety problems (such as when working with electrical systems or dangerous chemicals). It is true that radiation in large amounts can cause illness and even death, but no harmful effects have been found to evolve from very small amounts.

Most small radiation sources are constant; for example, cosmic rays constantly bombard the earth from outer space, some material in the human body is radioactive, and radioactive elements (especially radium and uranium) are present in soils. Similarly, a person who lives in a brick house is exposed to more radiation than a person who lives in a wooden one. Radiation sources, such as luminous watch dials, medical and dental x-rays, and television sets, give off radiation that contributes to an overall radiation exposure level.

Considerable work in the field of radiological effects (on animals and certain occupational workers) and studies of the effects of nuclear weapons detonated since 1945, have led to the establishment of guidelines for safe exposure (dose) levels. These guidelines are generally believed to be conservative, and the levels sufficiently low to constitute an acceptable risk to human health.

Even so, exposure to radiation must be closely controlled and the use of radioactive sources restricted to those who demonstrate an ability and need to handle them. Authorization to possess and use radioactive sources is granted either by the Nuclear Regulatory Commission (NRC) or by "agreement states." Agreement states are those states in the country that have agreed to accept responsibility for radioactive control within their respective boundaries including, in many cases, x-ray and other medical instruments or machines.

The amounts of radiation used in performing normal laboratory experiments are relatively low levels. The exposure that an individual receives while performing normal laboratory experiments is essentially negligible in comparison to the normal total exposure; however, laboratory practices and procedures similar to those used in high-radiation-level nuclear facilities will be followed to instill correct work habits and an appropriate awareness in the student.

One primary safety objective of all personnel working in a radiation laboratory is to keep levels as low as practical to reduce the exposure. Usually, by strict compliance with basic laboratory principles, the actual radiation levels and concurrent exposure can be maintained well below levels established by regulations. In addition to the basic principles concerning radiation, other safety principles - such as those concerning electricity and chemistry - should also be observed. Each of the basic radiation principles will be discussed separately.

BASIC RADIATION PRINCIPLES

Radiation monitoring, or testing for intensity of radiation, must be conducted to ensure compliance with state and federal regulations.

CAREFUL MONITORING

Radiation monitoring is conducted to determine the radiation levels in various areas and the radiation exposures of the people who occupy these areas. The first is accomplished with instruments such as a portable survey meter (Figure 1-1-1)

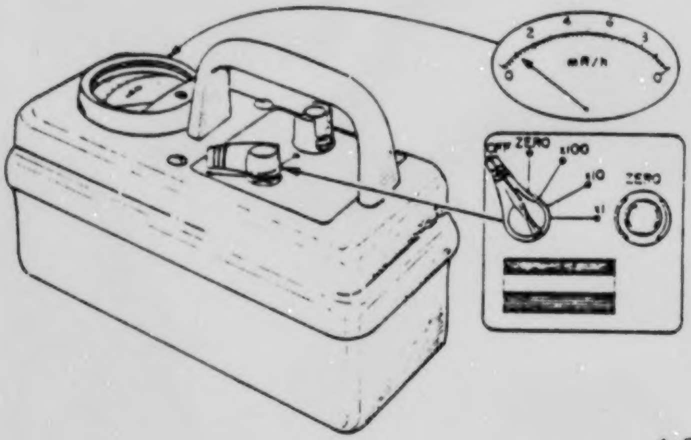

Figure 1-1-1.
Typical portable survey meter.

or an area alarm monitor (Figure 1-1-2). The second is usually accomplished with film badges (Figure 1-1-3), pocket dosimeters (Figure 1-1-4) or TLD, thermoluminescent dosimeters.

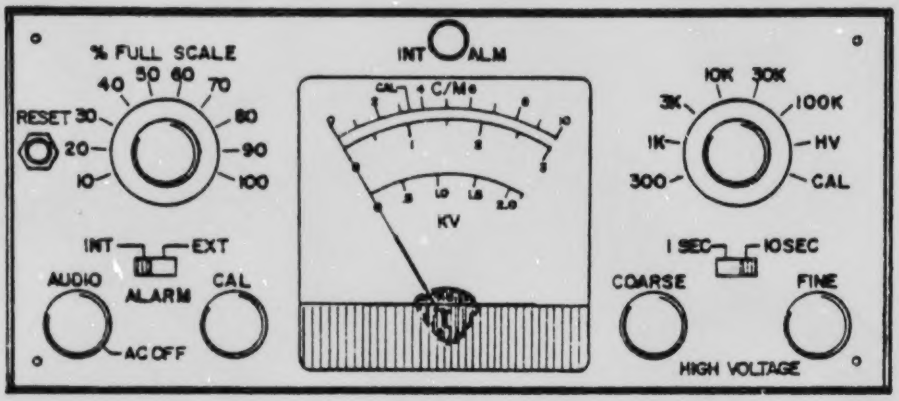
% FULL SCALE
10
20
30
40
50
60
70
80
90
100
RESET
INT
EXT
ALARM
AUDIO
AC OFF
CAL
INT
ALM
CAL
C/M
0
2
4
6
8
10
1
2
3
.5
1.0
1.5
2.0
KV
300
1K
3K
10K
30K
100K
HV
CAL
1 SEC
10SEC
COARSE
FINE
HIGH VOLTAGE

Figure 1-1-2. Typical area alarm monitor.

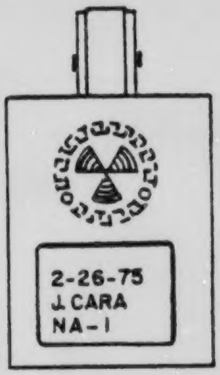
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Figure 1-1-3.
Typical film badge.

Film badges and dosimeters are worn on the body of a person to be monitored. These items are discussed in more detail in Module 1-2.

It is imperative that accurate records of radiation

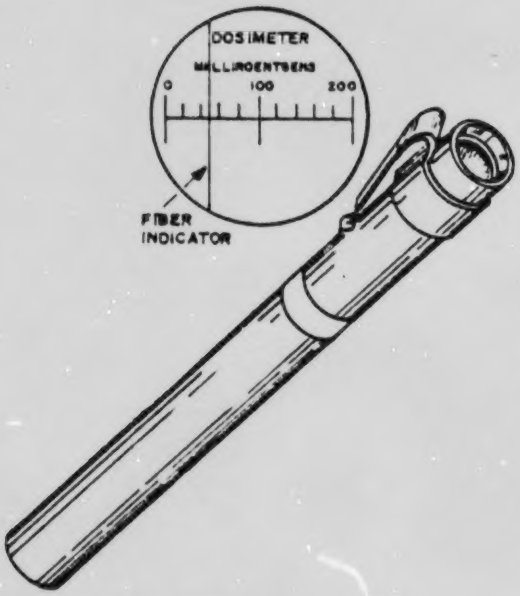


Figure 1-1-4.
Typical pocket dosimeter.

levels and personal exposure be kept by individual laboratory personnel. These records are necessary to demonstrate compliance with regulations and to maintain a complete history of personal radiation exposure. Film badges or dosimeters are usually required to be worn during a laboratory period. If required, the instructor will discuss correct procedures. At the conclusion of a laboratory period, hands, shoes and clothing should be monitored before leaving. The instructor will demonstrate proper technique.

SOURCE STRENGTH CONTROL

The amount of emitted radiation should be controlled to the minimum needed to conduct the desired exercise. For radioactive materials, the amount of radiation is controlled by limiting the quantity to that necessary to perform the task. For most laboratory experiments, only minute quantities are required - quantities so small they may be exempt from NRC or agreement state licensing.

These minute quantities present no great radiation hazard; however, they should be handled with care and respect, just as with all laboratory chemicals. For x-ray and other radiation producing machines, emissions can be controlled by machine adjustment, installation design and shielding (and frequent checks for license compliance).

EXPOSURE DURATION

Exposure to a radiation source should be limited to the time necessary to conduct the desired experiment. The amount received by personnel is directly related to the time exposed. For example, the amount received in two hours is twice that received in one hour (from a constant power radiation source). Normally, time of exposure may be controlled effectively if work is planned in advance and by making trial runs without the radioactive material.

DISTANCE FROM SOURCE

The distance between laboratory personnel and radiation sources should be as great as possible. Distance reduces radiation exposure by absorption in the intervening air as well as by geometric reduction (similar to the decrease in intensity of light with distance from the sun).

Remote handling devices (Figure 1-1-5) should be used when practical. These devices normally provide over a meter of separation. Practice with nonradioactive substances can develop skill in the use of remote devices. Sources should also be handled at arm's length, since human extremities can withstand more radiation than can the body proper.

SHIELDING

Shielding is a fourth factor by which one can attenuate

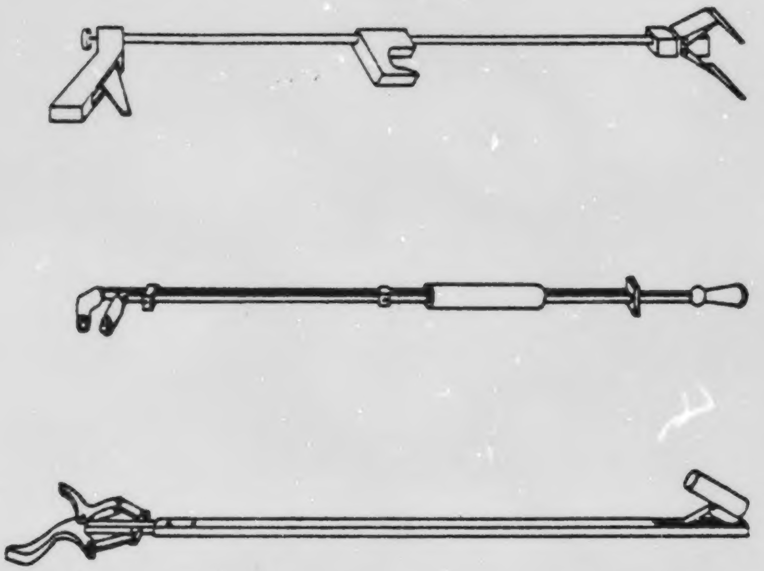


Figure 1-1-5. Typical remote handling devices.

or reduce radiation level and control personal exposure levels. Shielding is accomplished by putting an absorber in the path between a source and an individual to stop some fraction of the different types of radiation. (In this regard, air can be considered a type of shielding.) The effectiveness of shielding is usually measured as how much absorption takes place per unit thickness of shielding material.

HANDLING AND CONTAINING RADIOACTIVE MATERIAL

Proper laboratory techniques require knownig correct procedures for handling and containing particular radioactive materials and exercising care and good housekeeping in carrying out the job. Care should be given to minimizing the amount of radiation or exposure level and to effectively containing the radioactive material.

RADIATION SIGNS AND SYMBOLS

Radiation areas and radioactive materials must be properly and carefully marked with signs, labels or tapes that prominently display the appropriate radiation hazard symbol (Figure 1-1-6) indicating the degree of hazard. Specific requirements concerning the display of this symbol are given in state and federal regulations, and will be covered in later courses.

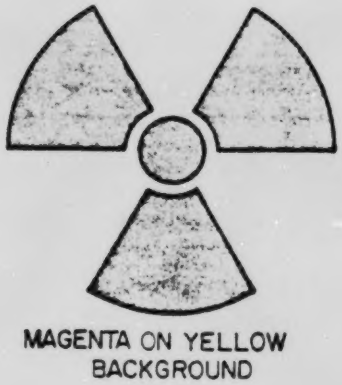


Figure 1-1-6.
Conventional radiation hazard symbol.

Plastic, two-strand rope (one yellow, one magenta) is used to rope off areas of high-radiation level or contamination. Passage within the roped-off area must be made only with the consent of the instructor. A tag (Figure 1-1-7) shall be attached to the rope, identifying the specific hazard, the date and the person affixing the tag. Containers with radioactive materials must be properly labeled with pertinent information (as indicated in Figure 1-1-8).

A label must be carefully attached so that it will not fall off. Other signs, such as those in Figure 1-1-9, are also used to denote radiation hazards.

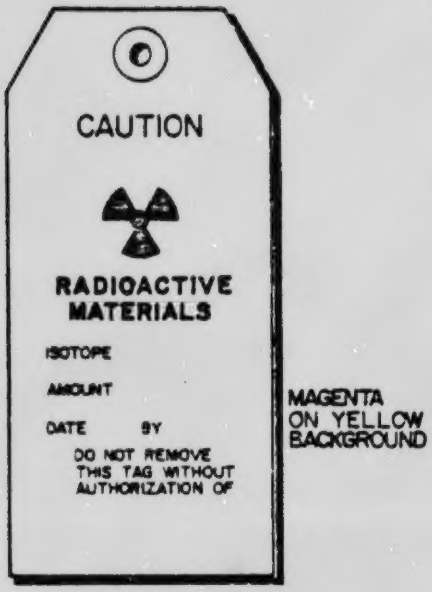
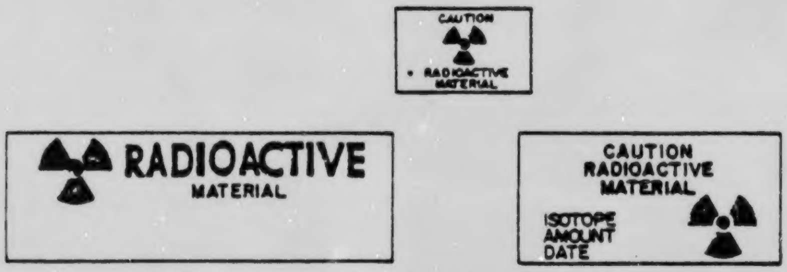

CAUTION
RADIOACTIVE MATERIALS
ISOTOPE
AMOUNT
DATE BY
DO NOT REMOVE THIS TAG WITHOUT AUTHORIZATION OF
MAGENTA ON YELLOW BACKGROUND

Figure 1-1-7. Hazard area tag.


CAUTION
RADIOACTIVE MATERIAL
RADIOACTIVE
MATERIAL
CAUTION
RADIOACTIVE
MATERIAL
ISOTOPE
AMOUNT
DATE

MAGENTA ON YELLOW BACKGROUND

Figure 1-1-8. Labels for radioactive containers.

PROTECTIVE CLOTHING

To prevent contamination of the person, rubber or plastic gloves should always be worn while handling radioactive materials in the radiochemistry laboratory. The rubber or plastic gloves must never be worn in the counting room because

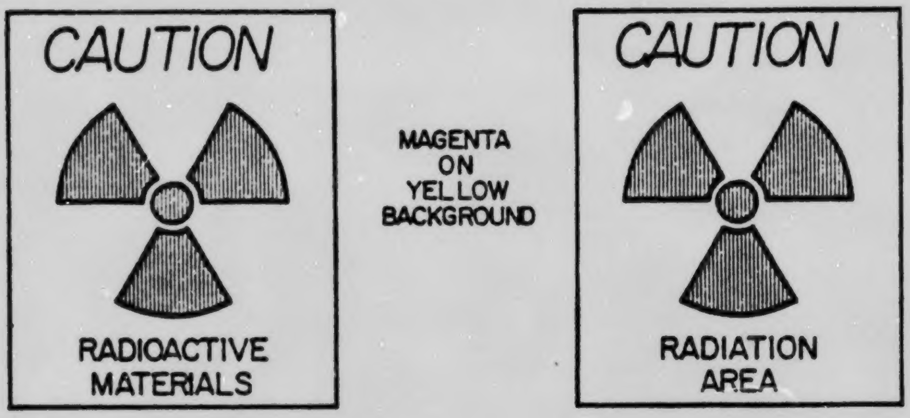


Figure 1-1-9. Radiation signs.

they could contaminate the counting equipment. If gloves are not to be discarded at the completion of the sample preparation work in the radiochemistry laboratory, they should be washed (while still being worn). The gloves should then be surveyed and removed.

A knee-length laboratory coat (generally white) should also be worn in the radiochemistry laboratory while handling radioactive materials to protect clothing from contamination. As in any chemistry laboratory, safety eyeglasses and safety shoes are usually required. Special protective clothing, such as shoe covers, plastic suits and respirators may be required during special decontamination operations.

No special protective clothing is required in the counting laboratory.

DISPOSAL OF RADIOACTIVE WASTE

Radioactive waste, simply stated, is radioactive material for which there is no further use (such as that resulting from decontamination or from completed experiments).

It must be properly disposed of by following strict state and federal regulations. Use is made of natural radioactive decay and dilution wherever possible.

All solid radioactive waste should be placed in specially designated waste containers, preferably stainless-steel enamel paint or PVC (polyvinyl chloride) plastics and lined with disposable polyethylene or coated paper bags. The radioactive material will undergo natural radioactive decay while in the container. This container should have a proper warning label to differentiate it from containers for all other solid wastes.

The instructor will ultimately dispose of the solid radioactive waste, either by transferral to a nonradioactive storage container, by incineration (if allowed by NRC) or by burial. The method will depend on radiation level and radiation type, in accordance with appropriate regulations and procedures.

Radioactive liquid wastes should be collected in a special bottle, usually filled with absorbent material, affixed with the proper warning label. The liquid will be held as long as practical to allow for radioactive decay. Periodically, the instructor will discharge liquid wastes to the public sewer system (if within NRC guidelines), being careful to dilute the waste with large volumes of water.

The amounts of radioactivity present in most laboratory exercises are so low that, under normal circumstances, waste disposal is not a problem. It may be advisable for schools, with separate disposal plants, to take liquid wastes to an area with an ordinary sewage system.

SHIELDING

Shielding materials, such as lead or concrete, should be placed between the radioactive source and personnel where practical. Shielding attenuates (reduces) the radiation by absorption. The particular shielding material and thickness to be used depends on the type and strength of the radiation. Design of an adequate shield for a particular application will be studied in a future module.

Radioactive material should be stored in a specialized storage container when not in use. This container should then be kept in a locked storage cabinet to prevent pilferage. Figure 1-1-10 shows typical lead storage containers. Often it is desirable to place the radioactive material inside special lead shield containers during counting to reduce the background radiation (Figure 1-1-11).

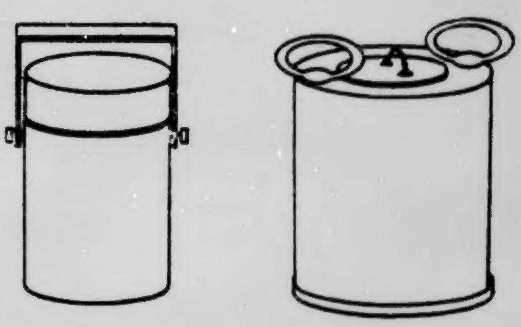


Figure 1-1-10.
Lead-wall storage containers.

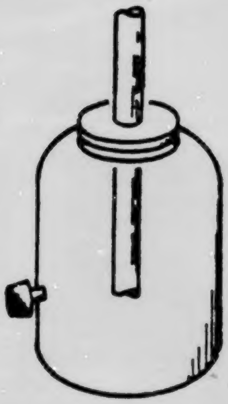


Figure 1-1-11.
Lead shield container
for counting.

DECONTAMINATION

To "contaminate" means to "make unfit" by introducing an undesirable material into an area; "decontamination" is the process of removing this material. In this context, *decontamination* is the process of removing radioactive materials from an area where it presents a hazard or problem to a location where it is acceptable. Decontamination is needed, not only to protect health, but also to prevent raising radioactive background in the laboratory to unacceptable levels. The procedure for decontaminating an area in which a radioactive material has been spilled is as follows:

Notify the instructor.

Rope off the area (to keep the liquid from being tracked to other areas, if the spill is on the floor).

Survey area with appropriate instruments to find contaminated spots and, later, to determine if spots have been cleaned satisfactorily.

Wear protective clothing and respirator as required for excessive radiation levels (determined by instructor).

Wipe up excessive liquid with absorbent materials, such as paper towels. Be sure to wear rubber or plastic gloves and use remote handling devices or tongs, if suitable.

Scrub contaminated area with detergent solution.

Place contaminated materials (liquids, paper towels, etc.) into proper, designated receptacles. The instructor may determine that radiation levels permit direct disposal to the environment.

Monitor protective clothing to determine if any contamination has taken place and if disposal is needed.

Wash hands with soap and water.

Monitor laboratory personnel to insure that no contamination remains.

Pipettes, other glassware and apparatus that has been contaminated through normal use should be placed in an area designated by the instructor. These items will be decontaminated by methods as directed by the instructor.

LABORATORY PRACTICES

Nuclear science laboratories are usually divided into two areas:

1. Sample preparation area (or radiochemistry lab).
2. Counting area, where radiation measurements of radioactive materials are made.

It is absolutely essential that the counting area be kept free from contamination so that instrument operation is not adversely affected. To avoid such a contamination problem, all sample preparation work must be performed in the sample preparation area.

Good laboratory practice prohibits smoking, eating or drinking within the radiochemistry or counting laboratory areas (because of the possibility of ingesting radioactive material into the body by way of smoke, food or drink. Smoke, food or liquid could carry a small fragment of radioactive material into the human body. Hazards from radiation taken internally are much greater than those from external radiation because of increased proximity to sensitive organs and the possible concentration of radioactive materials in a specific location within the body.) Special areas in the laboratory complex may be set aside for smoking, eating and drinking. Note: Always wash hands before going to these areas.

After each radiochemical experiment is finished, first survey, then isolate contaminated equipment, then wash the laboratory area where the work was performed. The area must be cleaned and all equipment washed. Washed glassware and utensils should be segregated until checked for radioactivity. All areas that might have become contaminated (i.e., table top, sink, floor) should be monitored.

Safety rules that apply to the handling of a laboratory chemical include:

Use double barriers to ensure containment.
Handle liquids only over catch pans or absorbent paper.
Handle volatile materials under a hood or in a glove box.
Pipette by other than oral technique.
Keep containers closed when not in use.
Avoid direct skin contact.
Never transport radioactive materials in uncapped or uncovered containers.
Always label containers.
Report all spills to the instructor immediately.

GENERAL SAFETY RULES

General safety rules for chemistry and electronics laboratories also apply to radiation laboratories. Potential hazards exist, involving high-voltage electricity and dangerous chemicals, and laboratory personnel must constantly be aware of these hazards. To prevent accidents, it is imperative that laboratory areas be kept clean and orderly.

The following general safety rules are to be adhered to strictly:

Work areas must be kept uncluttered.

Floors must remain free of tripping hazards, such as books, electrical cords and soft drink bottles.

Electrical cords must be in good condition, with no broken insulation.

High-voltage hazards must be identified.

Electronic tubes, including GM tubes, must be replaced only after the high-voltage power supply has been turned off and any residual charge dissipated.

Laboratory glassware must not be stored in cabinets or drawers with metal objects.

Cigarettes and matches must not be thrown in trash cans.

Horseplay must be disallowed.

All accidents, including minor cuts and scratches, must be reported to instructor immediately.

SPECIFIC SAFETY RULES

In addition to the general safety rules, specific safety rules are also established for radiation laboratories. These specific rules are necessary to protect the health of laboratory personnel and the general public from radiation hazards:

No eating, smoking or drinking in the radiation labs.

Knee-length lab coats must be worn in the radiochemistry lab.

Rubber or plastic gloves must be worn while handling radioactive samples in the radiochemistry lab.

Gloves must not be worn in the radiation counting lab unless they are required (e.g., in cleaning up a spill).

Film badges or dosimeters may be required in the radiation labs, as dictated by applicable regulations.

Hands, shoes and clothing must be monitored when leaving the radiation labs.

Hands are to be washed after handling radioactive samples in the radiochemistry lab.

Personal exposure should be minimized by keeping time to a minimum, and distance from the source to a maximum.

Shielding should be used when appropriate.

Source strength should be only as great as needed to perform the experiment, insofar as is feasible.

A roped-off area is not to be entered without prior approval from instructor.

Labels are placed on all containers of radioactive materials.

All radioactivity is handled over some disposable material, or over metal trays, in the radiochemistry laboratory.

All solid radioactive wastes are discarded in the properly marked receptacle. Never put solid radioactive waste in ordinary waste containers.

All liquid radioactive wastes are discarded in properly marked receptacles. Never dispose of radioactive liquids directly in the sink or sewer system without prior approval (or accomplishment by) instructor.

Radioactive liquids are never carried into the counting lab unless they are being specifically used in the experiment.

All spills and other accidents are reported to the instructor immediately.

Radioactive material must be stored and labeled in the proper storage cabinet or drawer upon completion of work.

If you are unsure as to the appropriate course of action to take in a given situation, always ask instructor before proceeding.

EXERCISES

1. Before entering a high-radiation area, Worker A picks up a dosimeter that indicates 10 mR. Two hours later, when A leaves the area, the dosimeter is removed and checked; it now indicates 90 mR.
   What is A's accumulated dose for the two-hour period?
   What is the hourly dose rate?
2. While checking the radiation level in the reactor containment area, B notices that the radiation detector indicates 100 mR/hr, with the range selector switch on position x 10. What is the actual dose rate in mR/hr?
3. If the dose rate in an area is 200 mR/hr and the supervisor tells A to receive only 100 mR while in the area, how long can A stay in the area?

MATERIALS

1	Pocket dosimeter*.
1	Film badge*.
1	Portable survey meter**.
1	Each, sheets of paper, wood and metal**.
1	Each, assortment of radiation signs and labels*.
20	Feet, radiation warning rope**.
1	Pair, shoe covers*.
1	Pair, rubber or plastic gloves*.
1	Knee-length lab coat*.
1	Box, absorbent materials such as paper towels.
1	Solid radioactive waste storage container.
1	Each, scrub brush, detergent and water pail.
1	Area alarm monitor.
1	Ruler or similar measuring device**.
1	Appropriate radioactive source**.

* Requires one per student.

** Requires one per group of two or three students.

PROCEDURES

DOSIMETERS

1. Pick up a pocket dosimeter (provided by instructor) and read value through the viewing window.
2. Record this initial reading and dosimeter serial number on Data Table 1-1-1.

3. Attach the dosimeter to your upper clothing and wear throughout the remainder of the lab period.
4. Read and record dosimeter reading at end of lab period.
5. Calculate difference between the final reading and the initial reading: This difference is the amount of radiation (exposure level) received during the lab period.
6. Be sure to replace dosimeter in its proper receptacle upon completion of the lab period. Check appropriate box on Data Table 1-1-1.

PORTABLE SURVEY METERS

1. Pick up a portable survey meter (provided by instructor); turn switch to "X1" setting. Record initial meter reading on Data Table 1-1-2. Disregard the units; they will be discussed later.
2. Place meter directly over radioactive source (provided by the instructor). Record the meter reading on Data Table 1-1-2.
3. Raise meter to 3, 6 and 12 inches above the source. Record the meter reading at each level.
4. Lower the meter to 3 inches above source. Momentarily place your hand between the source and the meter - record meter reading.
5. In turn, place a sheet of paper, a piece of wood and a piece of metal between the source and the meter. Record readings in each instance, and thickness of each object.
6. Turn meter to "OFF."
7. Describe effect of increasing distance between source and meter.

8. Describe effect of placing various objects between source and meter; rank their effectiveness in shielding (1, 2, 3, 4, 5).

SIGNS AND LABELS

1. Obtain various types of radiation signs and labels from instructor, including a) warning tape: "Caution Radioactive Material," b) warning tape: "Caution Radioactive Material," with space for material, amount and date, c) warning tape "Radioactive Material," and d) prestrung tag: "Caution Radioactive Material."
2. Attach tapes and tag to Data Table 1-1-3.
3. Where applicable, write your name and today's date. Also, identify the radionuclide and amount (as given by instructor). These terms will be discussed in later modules.

The following drawings and discussions are to be placed on the appropriate Data Tables:

4. Draw a characteristic radiation symbol and identify its colors. (Draw two types of radiation signs.)
5. Discuss in what situation each tape and tag would be used.
6. What is common to all tapes, tags and signs?

DECONTAMINATION

1. Practice decontamination as described in this module: Use water as the radioactive spill. Note: student should wear shoe covers, gloves and a lab coat.
2. On a separate sheet of paper state how an actual decon-

tamination might be different from a practice one.

NOTE: Upon completion of these laboratory procedures, record dosimeter reading on Data Table 1-1-1; replace the dosimeter in proper receptacle. Check appropriate box on Data Table, indicating that the dosimeter has been replaced.

DATA TABLE

DATA TABLE 1-1-1

Serial Number	Dosimeter Readings	
	Beginning of Lab	End of Lab

Have you received any radiation? __________

Dosimeter placed in proper receptacle at end of lab (place check in box). ☐

DATA TABLE 1-1-2

Meter turned to "X1" range (place check in box). ☐

PORTABLE SURVEY METER READINGS

Initial reading ____________

Directly over source ____________

3 inches above source ____________

6 inches above source ____________

12 inches above source ____________

3 inches above source with objects between source and meter:

	Thickness	Reading	Effectiveness in Shielding (Absorption/Thickness)
Hand			
Paper			
Wood			
Metal			
Open (air)			

Meter turned "OFF" (place check in box). ☐

What is effect of increasing distance between source and meter? (Portable Survey Meters, No. 7)

What is effect of placing various objects between source and meter? (Portable Survey Meters, No. 8)

DATA TABLE 1-1-3

Attach tapes here (Signs and Labels, No. 2):

Attach tag here (Signs and Labels, No. 2):

Drawings (Signs and Labels, No. 4):

Discuss situations in which tape and tag should be used (Signs and Labels, No. 5).

What is common to these tapes, tags and signs (Signs and Labels, No. 6)?

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TEST

Matching

Read each definition in the left hand column. For each definition, write in the blank the letter of the appropriate term found in the right hand column.

____ 1. The radioactive solid or liquid material resulting from decontamination or from completed experiments.

____ 2. Cleaning of a spill of radioactive liquid or of radioactive solid waste

____ 3. The use of portable survey meters, film badges or pocket dosimeters, or an area alarm monitor to determine radiation in various areas or the radiation exposures of people who occupy those areas.

____ 4. Those states in the U.S.A. that have agreed to accept responsibility for radioactive control within their respective boundaries.

____ 5. A description of materials that emit their energy in the form of electromagnetic radiation or particles.

____ 6. Release of electromagnetic waves or particles

a. decontamination

b. radiation

c. radioactive waste

d. monitoring

e. radioactive

f. agreement states

g. radioactive decay

h. dose rate

7. List three characteristics of radioactive materials.

a. ____

____

b. ____

____

c. ____

____

8. Write the primary safety objective regarding radiation of all personnel working in a radiation laboratory.

____

9. Draw the characteristic radiation hazard symbol and identify the appropriate colors.

10. List five practices that ensure minimum exposure to radiation in handling and containing of radioactive materials.

a. ______________________________________

b. ______________________________________

c. ______________________________________

d. ______________________________________

e. ______________________________________

11. A pocket dosimeter indicated 30 mR upon entry into and 80 mR upon exit from a radiation area. How much radiation was received?

____

12. A portable survey meter indicates 2.5 mR/hr. The range selector switch is in the X100 position. What is the indicated dose rate?

____

13. What effect does increasing the distance between the source and the detector have on the radiation level? Circle the letter of the correct answer below.

a. radiation level increases
b. no effect; radiation level remains the same
c. radiation level decreases
d. sometimes increases, sometimes decreases

14. What effect does placing various materials between the detector and the source have on radiation level? Circle the letter of the correct answer.

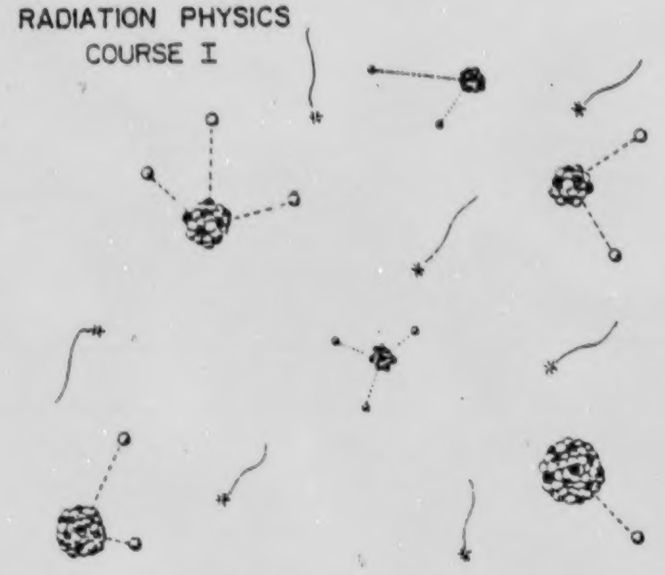
a. no effect on radiation level
b. lowers radiation level
c. raises radiation level
d. sometimes increases, sometimes decreases

15. Write the major steps involved in decontamination after spilling a radioactive liquid on the laboratory floor.

a. ______
b. ______
c. ______
d. ______
e. ______
f. ______
g. ______
h. ______
i. ______

NUCLEAR TECHNOLOGY

MODULE 1-2 BASIC RADIATION DETECTION AND MEASURING EQUIPMENT


RADIATION PHYSICS
COURSE I

COURSE MODULES

COURSE 1 RADIATION PHYSICS

MODULE 1-1	Introduction to Radiation Laboratory Safety
MODULE 1-2	Basic Radiation Detection and Measuring Equipment
MODULE 1-3	Atomic Structure and Radioactivity
MODULE 1-4	Radioactive Decay and Half-Life
MODULE 1-5	Decay Processes and Schemes
MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

One property of nuclear radiation is that it cannot be detected with the unaided senses, except at extremely high and unsafe levels. It cannot be seen; it cannot be felt. Therefore, some other means of detecting and measuring radiation is necessary (to ensure that radiation levels do not exceed standards set for the protection of employees and the general public). Too, the many uses of radiation in science and industry necessitate some means for measuring radiation. For example, in the paper industry, paper thickness may be determined by passing radiation through a sheet of paper and measuring the transmitted radiation - a simple technique for maintaining quality control.

Radiation detection and measurement equipment consists of devices that respond to radiation - e.g., a detector - and equipment that measures the amount of radiation (a measuring system). Three basic systems for detecting and measuring radiation are discussed in this module:

Personnel monitoring devices.
Geiger-Mueller scaler-ratemeters.
Portable survey meters.

MODULE PREREQUISITES

The student must have taken and successfully passed a radiation laboratory safety examination.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define and briefly describe:
    - Ionization.
    - Film badge.
    - Dosimeter.
    - Scaler.
    - Ratemeter.
    - Count rate.
2. Perform the following tasks related to dosimeters:
    - Identify the parts of a dosimeter, including the insulator, frame, quartz fiber, air volume, lens, glass scale and barrel.
    - Describe and perform the charging of a dosimeter.
    - Describe the physical process of charging (i.e., what happens inside a dosimeter when it is charged).
    - Indicate the difference between "zeroing" and "calibrating" an instrument.
    - Describe the process that takes place when radiation enters a dosimeter. Include the movement of fiber and vertical hairline.
    - Calibrate a dosimeter (based on a given calibration curve) and plot an exposure dose versus a time curve. Describe the significance of the shape of the curve.
    - Relate accumulated "dose received" during an exposure period to a normal survey meter reading during the same period.
3. Perform the following tasks related to a scaler-ratemeter operated with a Geiger-Mueller probe:
    - Draw labeled figures of end-window and side-window

Geiger-Mueller probes; include both the metal cylinder and the gas-filled tube; state instances in which each should be used.

Differentiate between the functions of a scaler and a ratemeter; list the units of output of each. Indicate when each should be used.

Calculate count rate (in counts per minute) from scaler data. (Given: total counting time.)

Draw and label a typical scaler-ratemeter. Include the ratemeter, counter, detector voltage, count switch, reset switch and high-voltage adjuster.

Given: ratemeter reading and range switch setting. Determine count rate in counts per minute.

Given: counting period. Set time (either external or internal) and operate scaler correctly; include proper high-voltage adjustment and counter reset.

Define the function of a TEST switch; indicate an approximate number of counts for a specified counting period.

4. Perform the following tasks related to a portable survey meter:

Given: meter reading and range switch setting. Determine count rate in counts per minute (or mR/hr).

List at least four differences in operation and four differences in construction between a portable survey meter and a scaler-ratemeter.

Identify the main use of a survey meter; give its limitations.

RADIATION DETECTION

Because, in general, nuclear radiation cannot be seen, heard or felt, persons working around radiation must be provided with instruments that detect its presence, even at very low levels. Radiation detection instruments have been designed to detect each type of radiation and, when appropriate, measure radiation levels.

Several methods are used for detection. A large class of systems rely upon ionization. (Ionization occurs when radiation passes through a substance, causing the atoms of the substance to be split into electrically positive and negative parts called ions. These electrically charged ions are collected by the detector to indicate the presence of radiation.)

Three basic detection and measurement systems - each of which uses ionization - are discussed in this module:

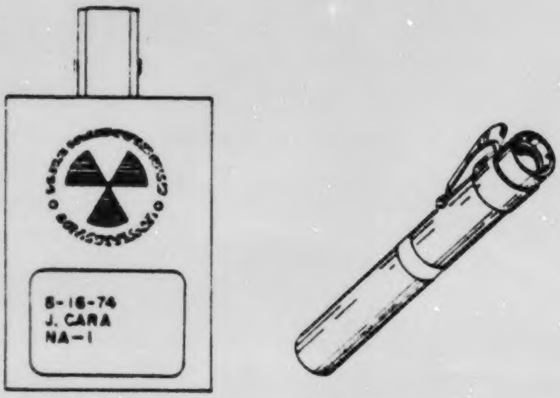
Personnel monitoring devices.
Geiger-Mueller scaler-ratemeters.
Portable survey meters.

PERSONNEL MONITORING DEVICES

The two most common types of personnel monitoring devices, film badges and pocket dosimeters (Figure 1-2-1)*, are usually worn on the body of workers. (These workers

---

* A third personnel monitoring device, the TLD (thermoluminescent dosimetry) is now in wide use and will be discussed later in another course.



Film Badge

Dosimeter

Figure 1-2-1
Two common personnel radiation
monitoring devices.

in the nuclear field must know the amount of radiation absorbed during a period of exposure.) Film badges and pocket dosimeters are small and lightweight and normally do not interfere with one's work. Unfortunately, neither device affords a highly accurate indication of exposure.

The film badge contains sensitive photographic film that darkens upon exposure to radiation. This darkening is caused by a chemical reaction that results directly from ionization produced by radiation. One disadvantage of a film badge is that exposure cannot be determined immediately because the film must first be developed (and analyzed with special procedures and equipment by trained individuals).

Film badges are usually obtained through a film-badge service offered by several supplier companies at a nominal cost. The service is available on a time-interval basis; the user wears the film badge for a month, for example, and ships it to the supplier for development and analysis. A replacement badge is provided by the supplier, and the process is repeated at desired time intervals. The supplier may also maintain permanent exposure records for each user, and notify each user immediately if an uncommon amount of radiation (dose) is detected by a badge. Each employer must also maintain records of personnel exposure.

NOTE: Badge data has legal recognition and is the source of an individual's exposure history. Thus, one should be familiar with the limitations of these types of detectors, which - like TLD chips - are generally read "after the fact," that is, after exposure has taken place.

The pocket dosimeter applies the principle of discharging a pair of oppositely charged surfaces when the air between them has been subjected to ionizing radiation. Initially, a voltage of approximately 160 volts DC is applied across the two surfaces to create an electric field inside the dosimeter (Figure 1-2-2A). When radiation enters the chamber, air molecules in the chamber are disassociated into positively and negatively charged particles, or ions (Figure 1-2-2B).

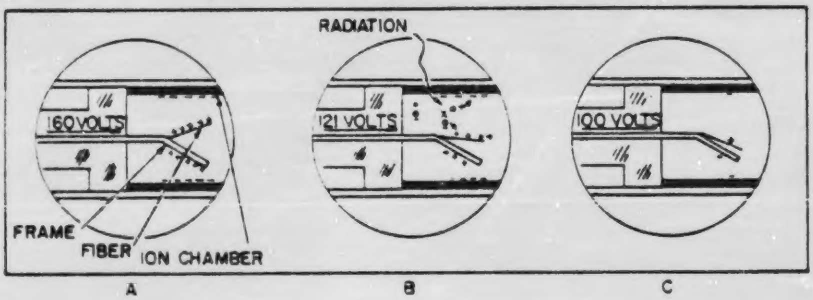


Figure 1-2-2. Principle of operation of the pocket dosimeter.

The positive ions move toward the negative surface, and the negative ions move toward the positive surface, because opposite charges attract (Figure 1-2-2C). The movement of these ions toward the surfaces reduces the charge difference between the fiber and the frame in the chamber, causing the fiber to move closer to the frame.

This fiber appears as a vertical hairline when the dosimeter is viewed from the end (Figure 1-2-3). The units, generally in milliroentgens (abbreviated mR), are discussed in a later module. In the example shown, the reading is 50 mR with a maximum meter reading capability of 200 mR.

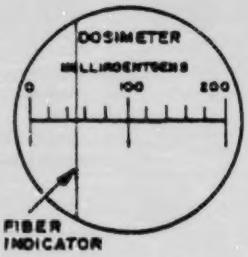

DOSIMETER
MILLIROENTGENS
0
100
200
FIBER INDICATOR

Figure 1-2-3.
Pocket dosimeter, end view, with fiber and scale.

Figure 1-2-4 shows the important features of a pocket dosimeter, including a lens for focusing an image of the fiber on the glass scale. When the dosimeter is charged,

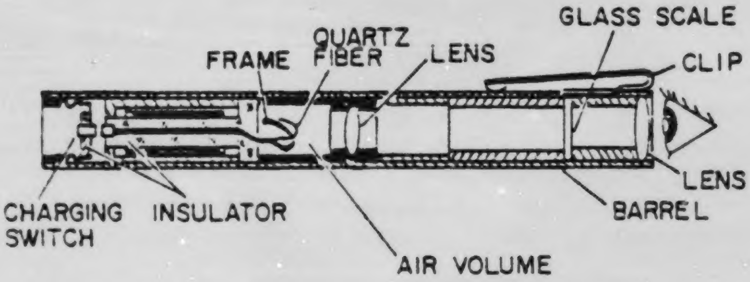

GLASS SCALE
QUARTZ FIBER
FRAME
LENS
CLIP
LENS
BARREL
CHARGING SWITCH
INSULATOR
AIR VOLUME

Figure 1-2-4. Cutaway drawing of a pocket dosimeter.

the positively charged fiber moves away from the positively charged frame toward the negatively charged chamber walls. As the charge on the dosimeter is reduced (by ionizing radiation), the fiber moves toward the frame, and the hairline (Figure 1-2-3) moves upscale.

The amount of radiation picked up by the dosimeter during a certain time interval equals the change in dosimeter reading. For example, if the dosimeter read 20 mR at the beginning of a 40-hour work week and 100 mR at the end, the total amount of radiation (dose) received is 80 mR.

The average exposure rate on the job may be calculated as follows:

$$\frac{\text{mR}}{\text{hrs}} = \text{mR/hr.}$$

Equation 1-2-1
(Equation = Eq.)

$$\frac{80\ \text{mR}}{40\ \text{hrs}} = 2\ \text{mR/hr.}$$

Dosimeter readings are often compared to known standard readings to check their accuracy. Actual readings can then be adjusted accordingly to record "true" values. This comparison is known as "dosimeter calibration," which will be performed in the Procedures section of this module.

Dosimeters, relatively unreliable, may produce false readings (from rough handling, reading errors, etc.). These devices are mainly used for gross, quick indications of radiation exposure, leaving more accurate readings to film badges and TLD's.

GEIGER-MUELLER SCALER-RATEMETER

One of the most frequently used devices for detecting and measuring nuclear radiation is the Geiger-Mueller scaler-ratemeter, frequently called a GM counter, or simply a Geiger counter. All such devices use a Geiger-Mueller tube (Figure 1-2-5) to detect particles of radiation.

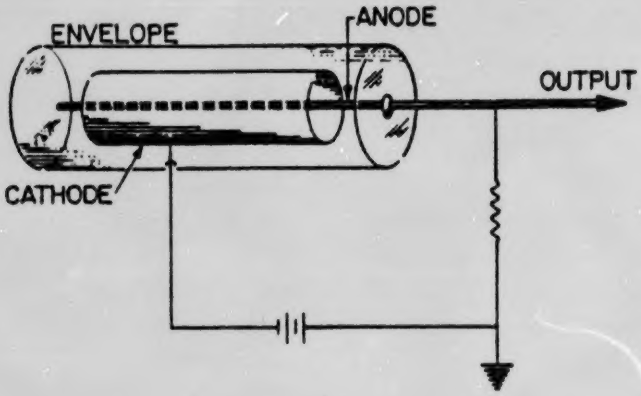
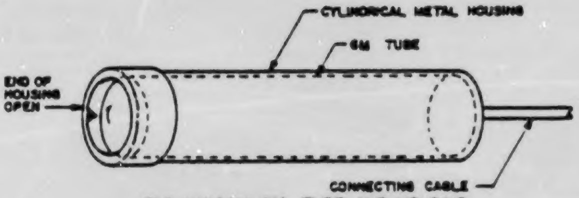


Figure 1-2-5. Basic gas-filled GM tube.

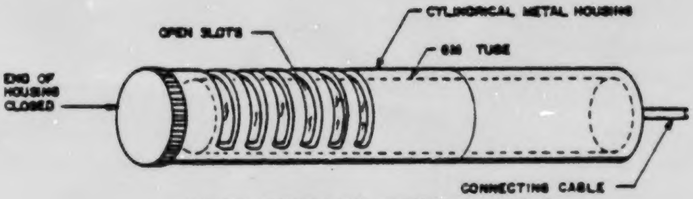
As discussed previously, radiation is detected by essentially measuring the ionization that occurs within the tube by collecting the resultant charge produced. The tube has a potential difference (voltage) of about 900 volts between the central anode wire (positive electrode) and outer cathode tube (negative electrode). The tube is filled with a low-pressure gas. When radiation enters the tube it ionizes the gas, producing oppositely charged ions, which are attracted to appropriate electrodes.

Geiger-Mueller tubes are generally available in two types: 1) side-window tubes and 2) end-window tubes (Figure 1-2-6). Each tube is contained in a metal housing for protection - the tubes usually have very thin walls, with wall thickness usually representing a compromise between required sensitivity (for detection) and necessary physical strength or durability. In general, the thinner the window wall, the more sensitive the tube is to weak radiation. The metal housing, together with the tube, makes up the "probe."


CYLINDRICAL METAL HOUSING
GM TUBE
END OF HOUSING OPEN
CONNECTING CABLE

END-WINDOW GM TUBE AND HOUSING

Figure 1-2-6.
Geiger-Mueller (GM) tubes
and probes.


CYLINDRICAL METAL HOUSING
OPEN SLOTS
GM TUBE
END OF HOUSING CLOSED
CONNECTING CABLE

SLIDE WINDOW GM TUBE AND HOUSING

NOTE: The Gieger-Mueller tube is the most sensitive part of a Geiger-Mueller scaler-ratemeter instrument and must never be touched with any object (not even the fingers), to prevent the tube wall or window from breaking and ruining the tube.

The side-window probe has a movable housing that can be rotated to completely cover the Geiger-Mueller window.

When completely covered, only the most penetrating radiation can pass through the metal housing and be detected. As will be shown later, use of this shield will permit the user to differentiate gamma from beta radiation.

The end-window probe is frequently used with a sample-pan holder (Figure 1-2-7) that contains shelves for radioactive samples. An extremely thin window permits greater sensitivity than could be obtained with a side-window probe.

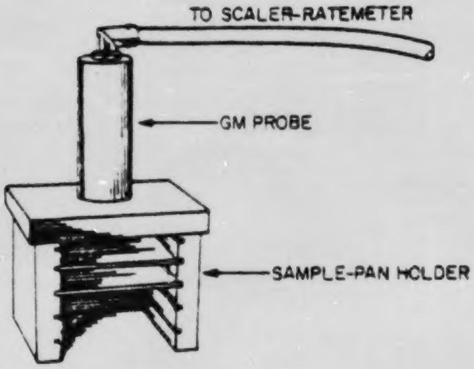


Figure 1-2-7.
End-window GM probe and sample-pan holder.

Advantages of the end-window probe and the sample-pan holder include: 1) samples may be placed on a higher (or lower) shelf to get a higher (or lower) count rate as desired; 2) use of a constant geometry; 3) absorption studies may be carried out with absorbers placed on shelves between the tube and the source.

A disadvantage is that the smaller end-window makes the tube less efficient than the side-window tube because, with the latter, a larger area is available for detection of penetrating radiation.

Devices that measure radiation in the Geiger-Mueller tube are called scalers or ratemeters. Some instruments, designed to measure only the total number of pulses registered during a particular time interval, are called scalers, or counters. Others, designed to measure only the count rate of pulses (counts registered per unit time) are called ratemeters. This count rate may be defined as follows:

$$\text{Count rate} = \frac{\text{total number of pulses registered}}{\text{total interval of counting}} .$$

Eq. 1-2-2

Ratemeter readings are usually expressed in counts per minute (cpm). Measurements made with a scaler can generally be compared with those made with a ratemeter as follows:

EXAMPLE:

Given: A scaler registers 50,000 counts during a 5-minute counting interval. Find the equivalent count rate with a ratemeter; assume that the same radioactive source, geometry and probe are used in each instance.

$$\text{Count rate} = \frac{\text{total number of pulses counted}}{\text{total time of counting}}$$

$$= \frac{\text{50,000 counts}}{\text{5 minutes}}$$

$$= \text{10,000 cpm.}$$

Some of the more sophisticated instruments display both the total number of counts and the count rate. Such instruments are called scaler-ratemeters (Figures 1-2-8 and 1-2-9).

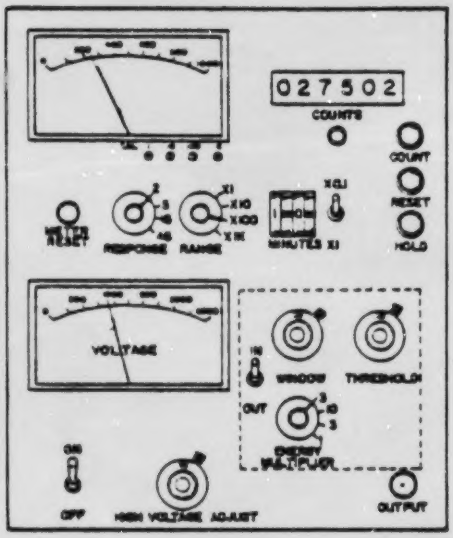

027502
COUNTS
COUNT
RESET
HOLD
METER RESET
RESPONSE
RANGE
X1
X10
X100
X1K
MINUTES
X1
VOLTAGE
IN
OUT
WINDOW
THRESHOLD
ENERGY MULTIPLIER
ON
OFF
HIGH VOLTAGE ADJUST
OUTPUT

Figure 1-2-8.
Typical scaler-ratemeter
(uses LED devices).

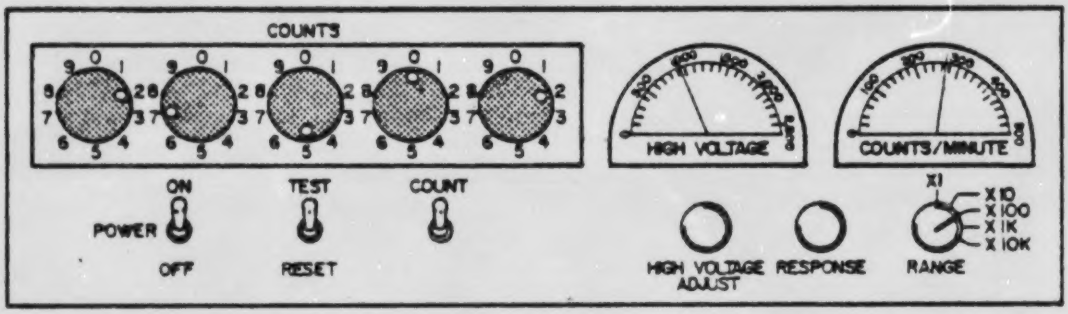

COUNTS
HIGH VOLTAGE
COUNTS/MINUTE
ON
POWER
OFF
TEST
RESET
COUNT
HIGH VOLTAGE ADJUST
RESPONSE
RANGE
X1
X10
X100
X1K
X10K

Figure 1-2-9. Scaler-ratemeter (uses Dekatron glow tubes).

Many companies produce such scaler-ratemeters, though they may differ somewhat in the following features:

Scaler or counter display. Some instruments (Figure 1-2-8) use light-emitting diodes (LED's). Some (Figure 1-2-9) use Dekatron glow tubes. Many older instruments used a display of neon bulbs (Figure 1-2-10). Other instruments use display lights with a mechanical register (similar to the odometer used on an automobile) because the array of display lights tends to be relatively expensive.

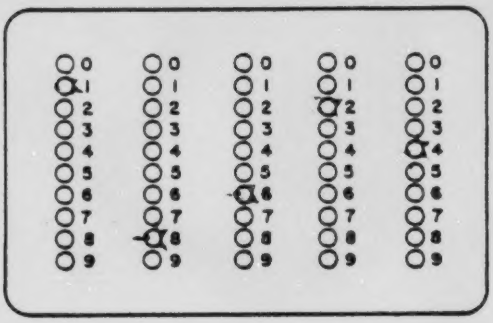


Figure 1-2-10.
Alternate counter display with neon glow tubes.

Timer. Some instruments (Figure 1-2-8) have a built-in timer. Others (Figure 1-2-9) rely on an external timer (Figure 1-2-11). Many external timers are connected to the scaler and automatically stop the counting after the preset time has elapsed. With some scalers it is possible to count for a preset number of counts, with counting time being the variable.

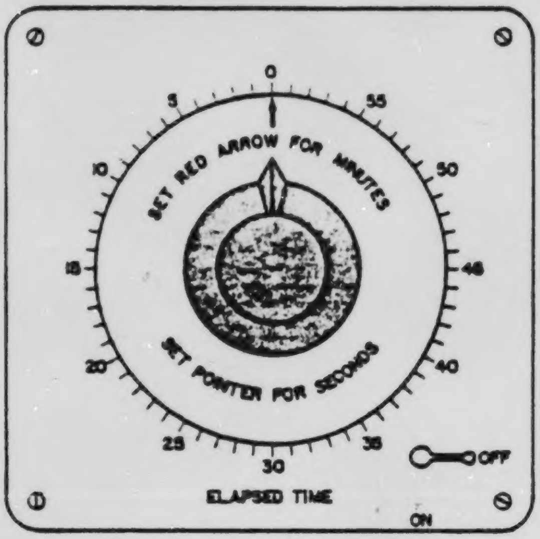

0
5
10
15
20
25
30
35
40
45
50
55
SET RED ARROW FOR MINUTES
SET POINTER FOR SECONDS
OFF
ON
ELAPSED TIME

Figure 1-2-11.
Typical external timer.

Ratemeter. Some instruments do not have a ratemeter. Others incorporate a ratemeter but no scaler, especially less expensive models. Display methods depend on the instrument's purpose. In general, a scaler is more accurate than a ratemeter.

Detector voltage. Some instruments have a meter that indicates voltage across the cathode and anode of the Geiger-Mueller tube. Others have the detector voltage and ratemeter on one meter, with a selector switch to change from one to the other. Some have no voltage indicator.

Test. Some instruments have a capability for testing electronic circuitry accuracy - they feed in a 60 hertz (cycles per second) signal from the line. (The ratemeter should read approximately 3600 counts/minute and the scaler should read 3600 counts for a one-minute counting period.)

PORTABLE SURVEY METER

This survey meter (Figure 1-2-12) is similar to the scaler-ratemeter discussed previously, with the following exceptions:

A ratemeter, but not a scaler, is used.

Usually it is portable and battery-powered. (Scaler-ratemeters are basically stationary laboratory instruments.)

Detector voltage is present and cannot be easily changed.

A detector tube may be an integral part of a survey meter.

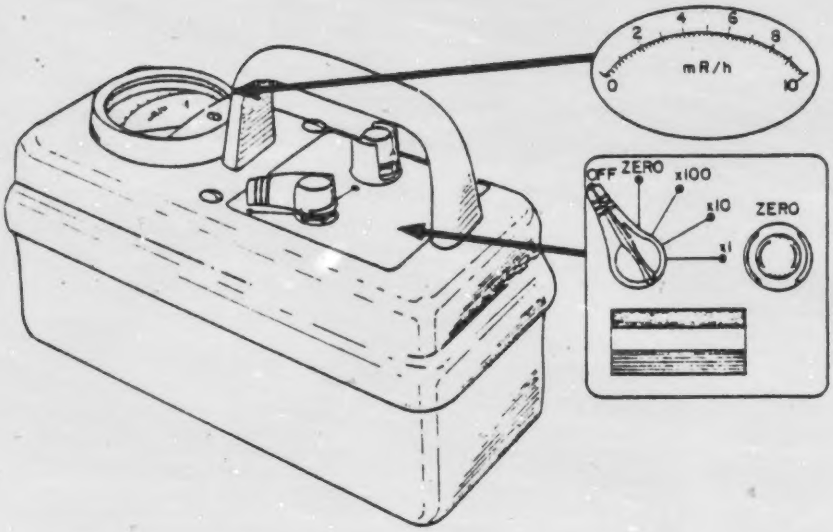


Figure 1-2-12. A typical portable survey meter.

Another type of portable survey meter has an external detector (or probe) similar to the one described previously. A cable connects this probe to the instrument case.

The survey meter is not a precise instrument for exposure rate measurements, although it can be used for this purpose. It is very useful, however, in detecting radiation, and is used to detect radioactive contamination of other instruments, work areas, clothing and personnel. Also it is used to detect radiation from spilled radioactive chemicals and leaks.

Frequently a survey meter is connected to a set of earphones or a speaker so that the output occurs as a series of audible "clicks." Earphones are especially useful when surveying an area suspected of radiation: 1) the person taking the survey doesn't have to watch the meter and 2) the audio response is much faster than the meter indication.

The audio amplifier is especially useful when personnel are not close enough to read the meter but can hear any sudden increase in counting rate. In such instances, the survey meter serves as an area alarm monitor.

EXERCISES

Employee A, using a GM detector and a counter-scaler indication system, is counting a sample of potentially radioactive water. If the sample is counted for 10 minutes and the total number of counts during that period is 2500, what is the count rate in counts/minute?

MATERIALS

Film badge*.
Dosimeter (direct-reading)**.
Dosimeter charger**.
Dosimeter calibrator**.
Scaler-ratemeter**.
Timer, if not integral to scaler-ratemeter**.
Side-window GM probe**.
End-window GM probe**.
Assortment of GM tubes**.
Sample-pan holder**.
Portable survey meter with built-in detector**.
Portable survey meter with external detector**.
Assortment of radioactive sources (license exempt)**.

---

* Requires one per student.
** Requires one per group of two or three students.

PROCEDURES

POCKET DOSIMETER CHARGE AND CALIBRATION

1. Remove protective cap from charging contact.
2. Place dosimeter over charging contact, viewing end up.
3. Remove dosimeter; record the serial number on Data Table 1-2-1.
4. View the dosimeter by looking through it at an external

light source with the scale horizontal and hairline vertical for proper reading; otherwise an inaccurate reading may be obtained.

5. Record initial reading on Data Table.
6. Press down firmly on dosimeter.
7. While looking through the eyepiece, adjust charger until vertical hairline reads zero. Quickly remove dosimeter. This adjustment may take several trys because the hairline tends to drift down scale.
8. Record zeroed reading on Data Table. (Ideally, this reading should be zero; if not, it should be close.)
9. Place dosimeter in dosimeter calibrator (as demonstrated by instructor). Record position number on Data Table.
10. Record readings on Data Table at five-minute intervals until the hairline goes off-scale.
11. Place dosimeter in charger; readjust hairline to zero. Record reading on Data Table.
12. Replace protective cap over charging contact.
13. Plot dosimeter readings on linear graph paper as a function of time. What is significance of the curve's shape? Write answer on Data Table.
14. Obtain calibrated rate of accumulation from instructor. How does this rate compare with actual data? How long did it take your dosimeter to reach full scale, compared with the accurately calibrated dosimeter? Write answers on Data Table.

SCALER-RATEMETER

1. Connect a GM probe to the instrument. Lay probe on table (be sure probe is far enough from edge to avoid its being knocked off table).

2. Turn instrument on; allow it to warm up for a time determined by instructor.
3. Adjust high-voltage control to value given by instructor. Record this value on Data Table 1-2-2. CAUTION: Exceeding this value could result in serious damage to the tube.
4. Measure natural background radiation twice, as follows (omit items denoted by an asterisk if the scaler does not have a ratemeter):

   Step 1. Press RESET button or switch.

   Step 2. Set timer to 5 minutes.

   * Step 3. Set RANGE switch on ratemeter to X1.

   Step 4. Press COUNT button or switch.

   * Step 5. If ratemeter reading is off-scale, change range until reading is on-scale.

   * Step 6. Record ratemeter scale reading and range scale.

   Step 7. After counting time elapses, record total number of counts and counting time in minutes.

   Step 8. Divide total counts by counting time. Record answer, which is background radiation level in counts per minute.

   Step 9. Repeat steps 1 through 8.

   Why are counts per minute different for the two series of counts?
5. If the scaler-counter does not have a TEST switch, proceed to next procedure (Portable Survey Meters).

   Step 1. Press RESET button or switch.

   Step 2. Set timer to 1 minute.

   Step 3. Press TEST button or switch.

   Step 4. Press COUNT button or switch.

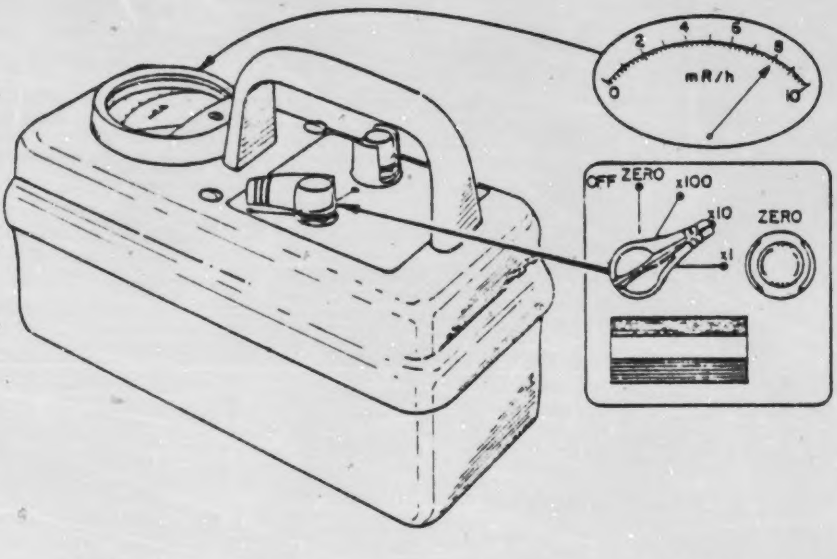
   Step 5. After counting time elapses, record total counts.

Because counting period was one minute, total counts equals count rate in counts per minute.

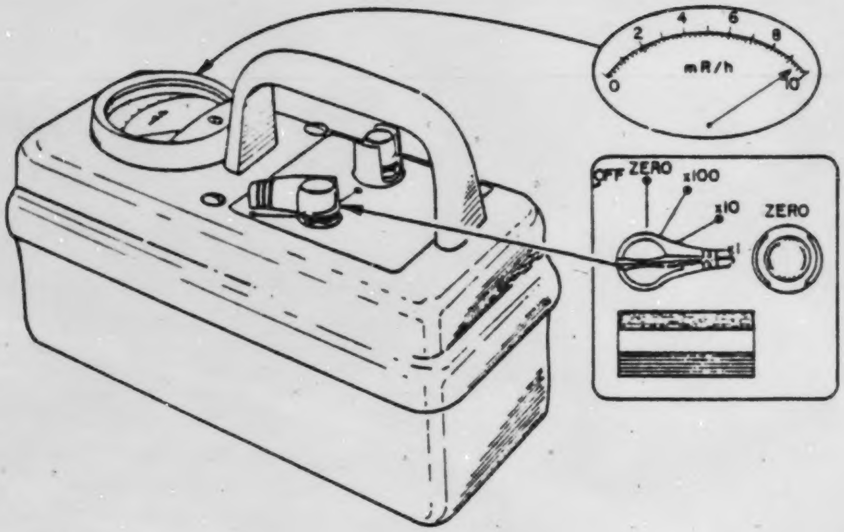
The count rate on TEST should be 3600 counts per minute. How does this compare with actual data (express as a percentage)?

PORTABLE SURVEY METER

1. As an exercise in meter reading, student should record (on Data Table 1-2-3) the count rate in counts per minute for each of the following ten cases. Remember to multiply meter reading by range reading.



1) ______________________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4
6
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mR/h
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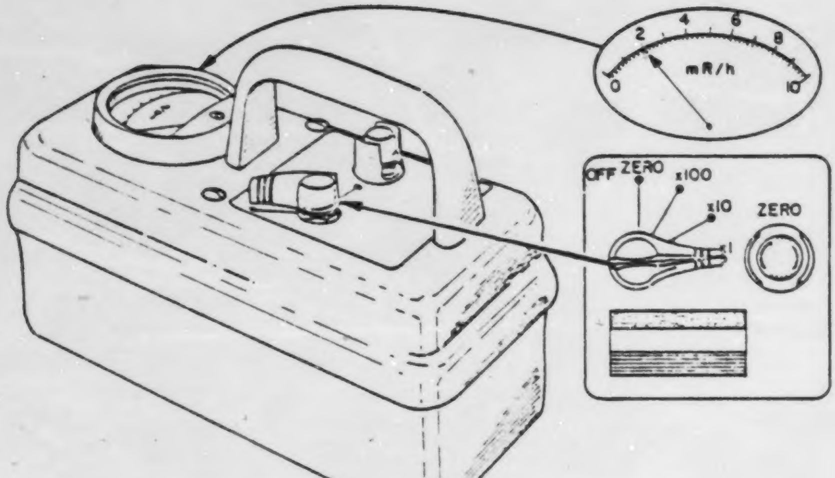
10
OFF
ZERO
x100
x10
x1
ZERO

2) ______________________________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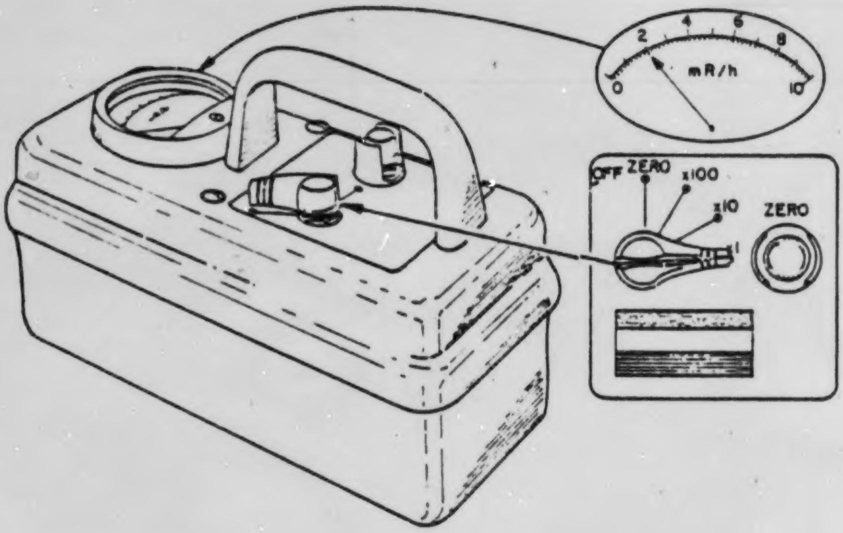
ZERO

3) ______________________________



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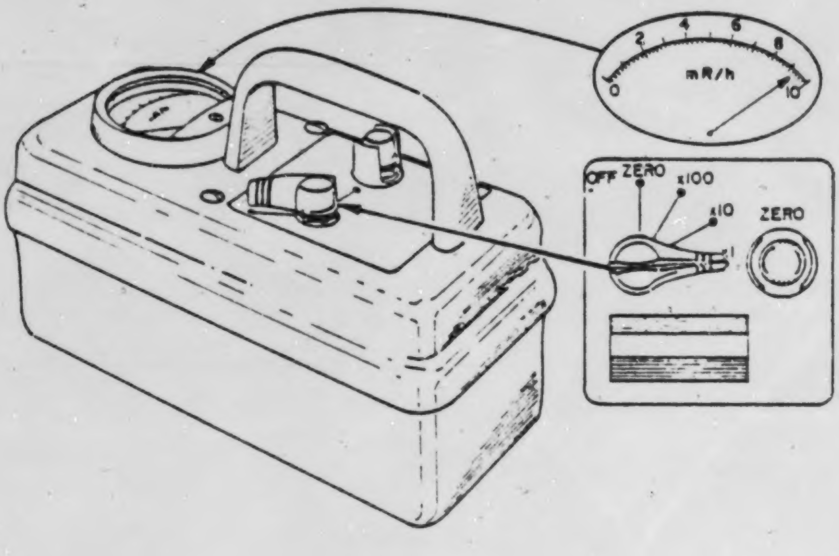
ZERO
x100
x10
x1
ZERO

4) ______________________________



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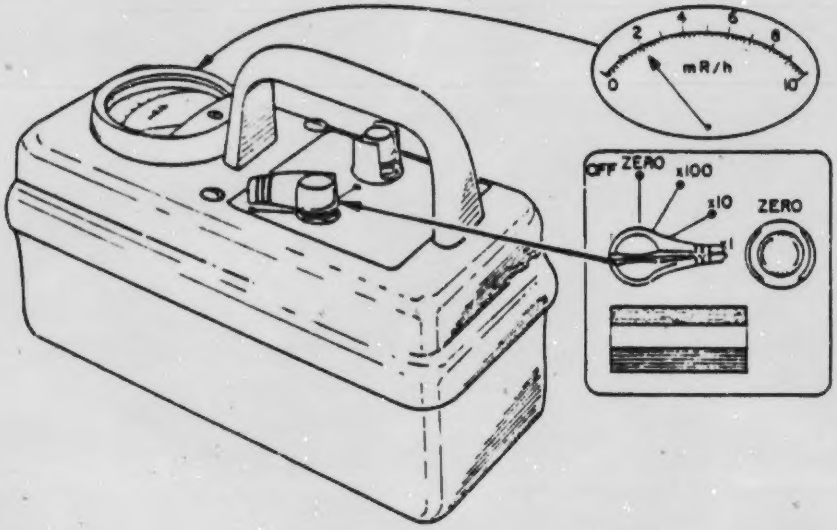
2
4
6
8
10
mR/h
OFF
ZERO
x100
x10
x1
ZERO

5) ______________________________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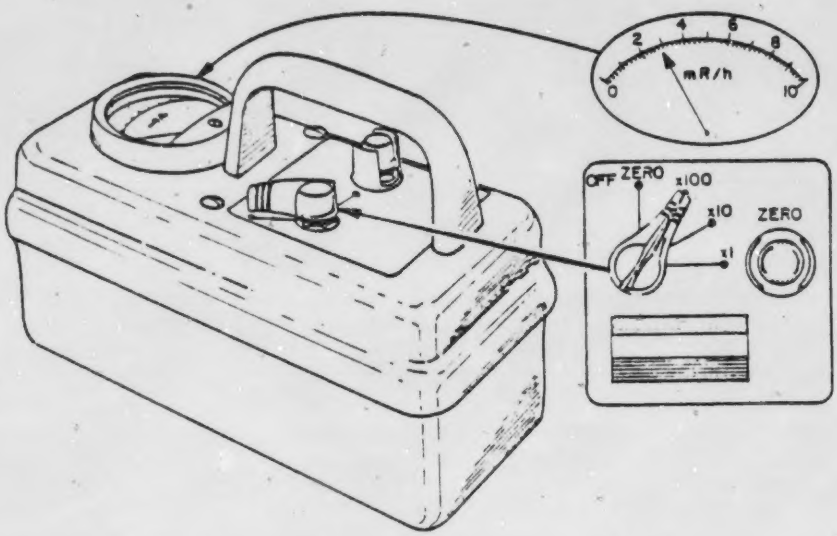
x10
x1
ZERO

6) ______________________________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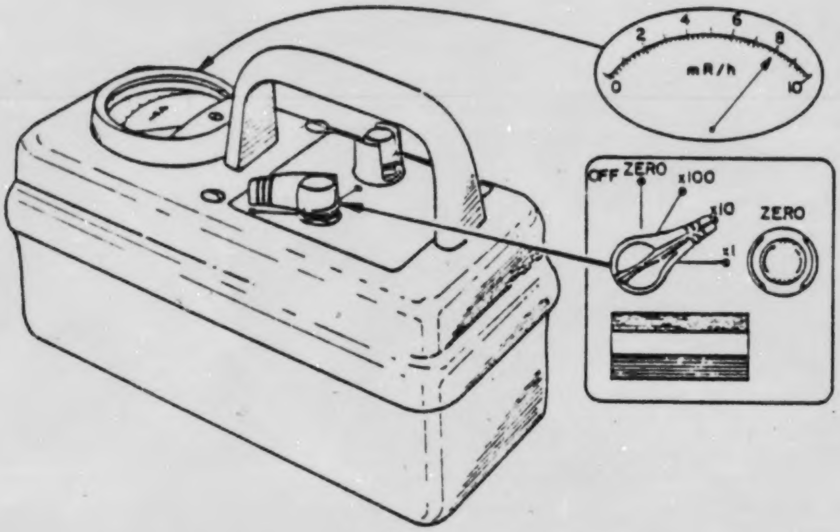
x100
x10
x1
ZERO

7) ______________________________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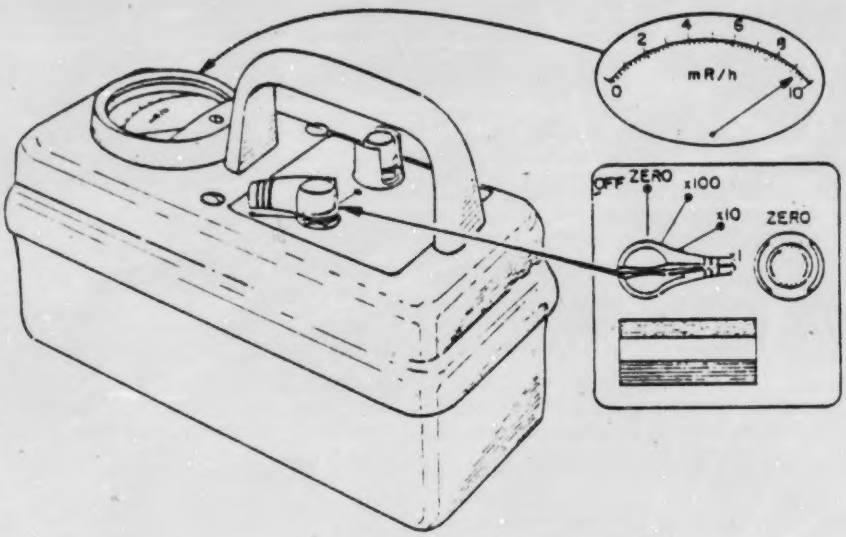
x100
x10
x1
ZERO

8) ______________________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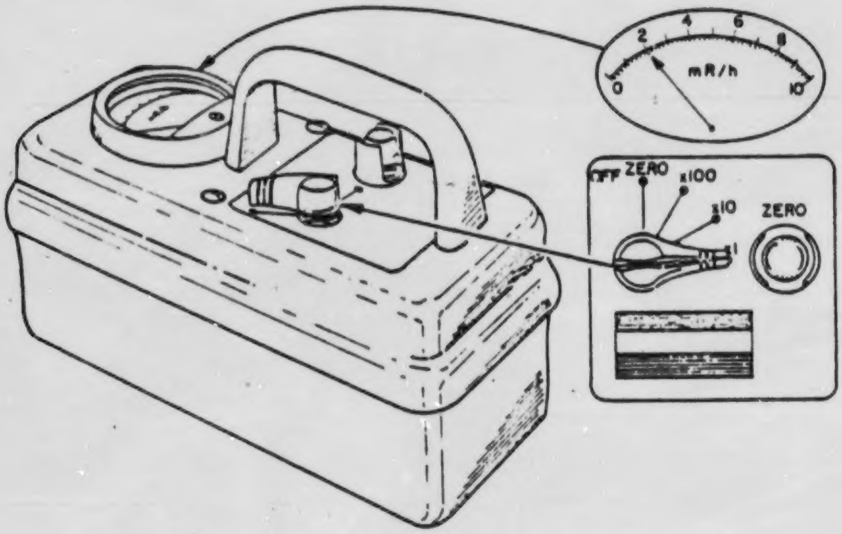
mR/h
OFF
ZERO
x100
x10
x1
ZERO

9) ______________________



10) ____________________

2. Obtain a portable survey meter; turn range switch to TEST. Record reading on Data Table. (Are batteries adequate? If not, notify instructor and see that batteries are replaced.)
3. Place survey meter over source (provided by instructor). If probe is external, place it (not the meter) over the source.
4. Turn range switch to ZERO; record reading.
5. With range switch still on ZERO, adjust ZERO knob so that reading is ZERO.
6. Record meter readings (all scales) on Data Table.
7. Which scale should be used for this source?
8. If time permits, allow instructor to hide a radioactive source somewhere in lab. Students should be able

to find source, using only survey meters. This exercise provides practice in locating unknown radioactive material.

DATA TABLE 1-2-1

1. Dosimeter serial number: ____________________
2. Initial dosimeter reading: ____________________
3. Zeroed dosimeter reading: ____________________
4. Calibration position: ____________________
5. Serial number: ____________________
6. Dosimeter calibration: ____________________

Minutes from Beginning	Reading

7. Zeroed dosimeter reading: ____________________
8. Protective cap placed over charging contact: ____________________
9. Dosimeters placed in storage case: ____________________
10. Significance of shape of curve:

11. Calibrated (predicted rate of accumulation)
_______________ mR/hr.

12. Comparison of predicted and actual data:

DATA TABLE 1-2-2

	1st count	2nd count
1. High voltage reading:		
2. Ratemeter scale reading:		
3. Range scale:		
4. Ratemeter reading (No. 2 x No. 3), cpm:		
5. Total counts:		
6. Counting time, minutes:		
7. Counting rate (No. 5 ÷ No. 6), cpm:		

8. Explain why counting rate is different for the two series of counts:

(Note: Go on to Data Table 1-2-3 if instrument has no TEST function.)

9. TEST - total counts: ____________

10. Counting time, minutes: ____________

11. TEST - count rate (No. 9 ÷ No. 10), cpm: ____________

12. Percentage difference between actual TEST counting rate (No. 11) and true counting rate, 3600 counts/minute:

$$\frac{\text{Actual} - 3600}{3600} \times 100\% = \_\_\_\_\_\_\_\_\_\_\_\_\%.$$

DATA TABLE 1-2-3
METER READING EXERCISE

	METER READING	x	RANGE READING	=	ACTUAL COUNT RATE (meter reading) x (range reading)
1		x		=	
2		x		=	
3		x		=	
4		x		=	
5		x		=	
6		x		=	
7		x		=	
8		x		=	
9		x		=	
10		x		=	

TEST reading:

Are batteries adequate? ____________

Meter reading on Zero scale: ____________

Meter reading on Zero scale after being zeroed: ____________

Meter readings - X1 scale: ____________

X10 scale: ____________

X100 scale: ____________

X1K scale: ____________

Which scale should be used in this case? ____________

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TEST

Circle the letter of the best response to each definition 1-6.

1. The process which occurs when radiation passes through a substance causing that substance's atoms to be split into electrically positive and negative ions.

   a. polarization
   b. conductivity
   c. ionization
   d. radiation

2. A personal monitoring device that uses a pair of surfaces which discharge positive and negative ions when the air between these surfaces is subjected to ionizing radiation.

   a. Geiger-Mueller tube
   b. film badge
   c. dosimeter
   d. scaler/ratemeter

3. A personal monitoring device that contains photographic film that darkens when exposed to radiation.

   a. film badge
   b. scaler/ratemeter
   c. Geiger-Mueller tube
   d. dosimeter

4. An instrument designed to measure the total number of pulses registered during a particular time interval.

   a. ratemeter
   b. oscilloscope
   c. transistor
   d. scaler

5. An instrument designed to measure only the count rate of pulses registered per time unit.

   a. ratemeter
   b. timer
   c. survey meter
   d. scaler

6. The total number of pulses registered divided by the total interval of counting:

   a. radiation level
   b. count rate
   c. current
   d. contamination

7. When a dosimeter is charged, what happens inside the dosimeter?

   a. the fiber moves toward the frame
   b. the frame moves toward zero
   c. the fiber moves away from the frame
   d. the frame moves away from the fiber

8. What process takes place when radiation enters a dosimeter?

   a. ionization caused by radiation discharges the fiber
   b. radiation adds to the charge, causing the fiber to move
   c. radiation striking the fiber imparts kinetic energy, thus moving the fiber
   d. polarization causes the frame to move toward zero and the fiber to move upscale

9. One major limitation of a dosimeter is:

   a. only gamma radiation can be detected
   b. an expert is needed to interpret dosimeter readings
   c. quartz fibers must be used, making a dosimeter very expensive to use
   d. rough handling or dust can cause it to produce false readings

10. One main use of the end-window Geiger-Mueller tube is:

   a. detection of penetrating radiation over large area
   b. to provide an audio response when radiation is detected
   c. absorption studies
   d. to calibrate pocket dosimeters

11. The function of the test switch on the scaler-ratemeter is to:

   a. determine the accuracy of the electronic circuitry
   b. determine the type of radiation being emitted
   c. indicate voltage across the cathode and anode of the Geiger-Mueller tube
   d. collect the charge produced by ionization

12. Which of the following statements best gives the primary use of a G-M survey meter?

   a. The survey meter is used in laboratory experiments with minute quantities of radioactive materials.

   b. The survey meter is used in area monitoring to measure radiation levels.

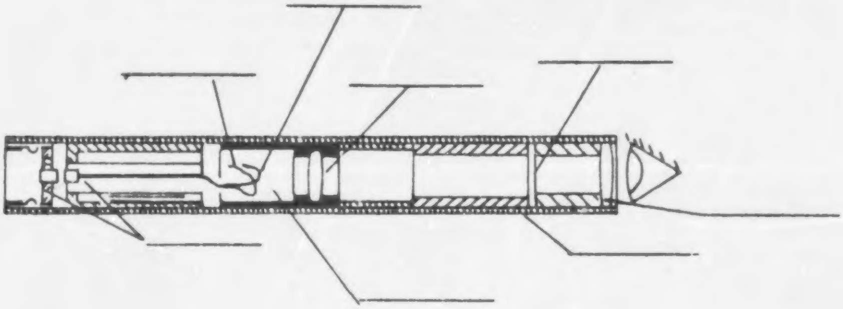
   c. The survey meter is used to provide the radioactive source for a scaler/ratemeter.

   d. The survey meter is used to tell how much radiation a particular person can tolerate without tissue damage.

13. Lable these parts of the drawing of a dosimeter.

   a. insulator
   b. frame
   c. quartz fiber
   d. air volume
   e. lens
   f. glass scale

   Place your answers in the appropriate blanks.



14. Write the four most important steps involved in charging a dosimeter.

   a. ____

   ____

   b. ____

   ____

   c. ____

   ____

14. (Continued)

d.

15. If a pocket dosimeter indicates toat 100 mR of radiation was recieved in 20 minutes, what is the average dose rate in mR/hr?

16. Calculate the count rate in counts per minute. Total number of counts: 25,000. Total counting time: 2 hours

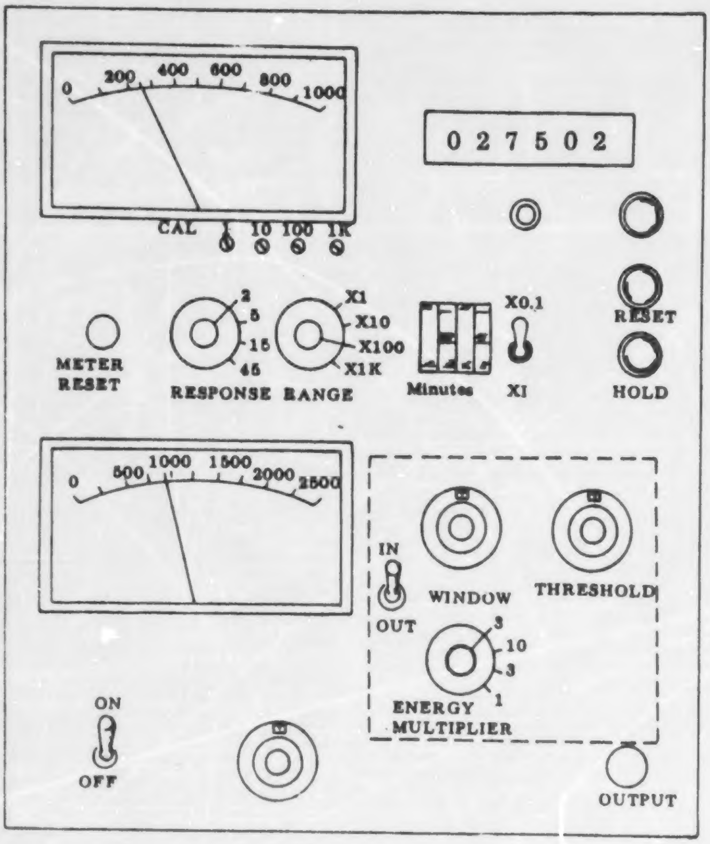
17. Given a ratemeter reading of 250 counts per minute and a range switch setting of X100, calculate the counts per minute.

18. If a dosimeter reads 10mR at the beginning of a 40 hour work week and 110mR at the end of the work week, what is the dose received? What is the average exposure rate on the job?

Dose Rate:
Average Exposure Rate:

19. A scalar registers 10,000 counts during a 2 minute counting interval. Assuming that the same radioactive source, geometry, and probe are used, what is the equivalent count rate with a ratemeter?

20. Given this drawing of a typical scaler-ratemeter, lable the following parts: number of counts, detector valtage, count switch, and high voltage adjust.


0
200
400
600
800
1000
027502
CAL
1
10
100
1K
2
5
15
45
X1
X10
X100
X1K
METER RESET
RESPONSE
RANGE
Minutes
X0.1
XI
RESET
HOLD
0
500
1000
1500
2000
2500
IN
OUT
WINDOW
THRESHOLD
3
10
3
1
ENERGY MULTIPLIER
ON
OFF
OUTPUT

Typical Scaler-Ratemeter

21. Given a G-M portable survey meter reading of 425 mR/hr and a range switch setting of X10, calculate the radiation level in mR/hr.

____

22. Write one main use for a survey meter in the laboratory?

____

23. What is the difference between zeroing an instrument and calibrating an instrument?

____

24. List two differences between a scaler-ratemeter and a survey meter.

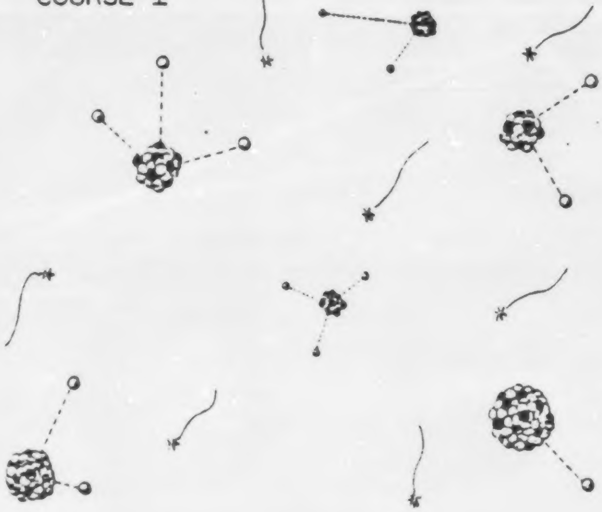
a. ______________________________

b. ______________________________

NUCLEAR TECHNOLOGY

MODULE 1-3 ATOMIC STRUCTURE AND RADIOACTIVITY

RADIATION PHYSICS
COURSE I



COURSE MODULES

COURSE 1 RADIATION PHYSICS

MODULE 1-1	Introduction to Radiation Laboratory Safety
MODULE 1-2	Basic Radiation Detection and Measuring Equipment
⇨ MODULE 1-3	Atomic Structure and Radioactivity
MODULE 1-4	Radioactive Decay and Half-Life
MODULE 1-5	Decay Processes and Schemes
MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
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INTRODUCTION

The release of nuclear energy results from certain transformations within the nucleus of the atoms. This energy release occurs in nuclear reactors where atoms are split (fission) as well as in many other radioactive processes. To understand how this release takes place and under what conditions, it is necessary to have an understanding of basic atomic structure and radioactivity, both of which are discussed in this module.

In the study of atomic structure and radioactivity, it is important to be able to measure the various types of radiation emitted by radioactive materials. In Module 1-2, the student was introduced to a Geiger-Mueller scaler-ratemeter and taught how to use it. In this module, the student continues to use the Geiger-Mueller (GM) scaler-ratemeter, measuring certain instrument characteristics.

MODULE PREREQUISITES

The student should have familiarity with operating procedures of Geiger-Mueller (GM) scaler-ratemeters, and should know and practice basic radiation laboratory safety.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Complete the following tasks:
    Give a one or two sentence definition of elements and atoms.
    Identify the three fundamental particles that form the atom; give the placement, charge and relative mass of each.
    Given a symbolic notation and a list of elements, identify the element, state its atomic number and mass number.
    Identify mass number, atomic number and the element from a given number of neutrons and protons and a list of elements.
    Define the terms "isotope" and "nuclide."
2. Given the appropriate equipment (including a GM scaler-ratemeter) or data, complete the following tasks:
    Plot a count-voltage curve by varying the probe voltage and identifying the GM plateau operating voltage, starting voltage, threshold and region of continuous discharge.
    List at least two advantages of operating the scaler-ratemeter with the voltage set within the Geiger-Mueller plateau region; also, explain why the instrument should not be operated with voltage set in the range of continuous discharge.
    Calculate gross count rate (total counts per unit time) from total counts and total counting time.
    Given a gross count rate, determine background counting rate and calculate net counting rate.

Diagram and label the four basic parts of a GM tube; list sequentially the seven steps describing how the tube functions.

BASIC ATOMIC STRUCTURE

All matter is composed of atoms. All atoms which have the same atomic number belong in a common classification known as an element (for example, oxygen or uranium).

ELEMENT

An element is a fundamental substance that cannot be changed into another fundamental substance by ordinary chemical or physical processes. For example, the element aluminum cannot be changed into the element gold by chemically mixing it with acids, alkalies or other substances, neither can aluminum be physically changed even though liquefied, vaporized or subjected to extreme pressures.

Or, consider the element carbon. Even though a mass of carbon may be heated to form a gas, it remains carbon. (Carbon gas can be converted back to its solid form.) Carbon enters into many combinations with other elements to form materials (chemical compounds), but other reactions can always reclaim the carbon from these materials. In this sense, carbon is a fundamental, unchangeable substance - an element.

The almost infinite variety of materials in the world is made up of combinations of these elements, more than 90 of which occur naturally. Another dozen or so have been produced artificially in recent years in nuclear reactors and particle accelerators. A complete list of elements and their chemical symbols is given in Table 1-3-1.

TABLE 1-3-1

LIST OF ELEMENTS

ATOMIC NUMBER	SYMBOLS	NAME	ATOMIC NUMBER	SYMBOL	NAME
0			52	Te	tellurium
1	H	hydrogen	53	I	iodine
2	He	helium	54	Xe	xenon
3	Li	lithium	55	Cs	cesium
4	Be	beryllium	56	Ba	barium
5	B	boron	57	La	lanthanum
6	C	carbon	58	Ce	cerium
7	N	nitrogen	59	Pr	praseodymium
8	O	oxygen	60	Nd	neodymium
9	F	fluorine	61	Pm	promethium
10	Ne	neon	62	Sm	samarium
11	Na	sodium	63	Eu	europium
12	Mg	magnesium	64	Gd	gadolinium
13	Al	aluminum	65	Tb	terbium
14	Si	silicon	66	Dy	dysprosium
15	P	phosphorus	67	Ho	holmium
16	S	sulfur	68	Er	erbium
17	Cl	chlorine	69	Tm	thulium
18	Ar	argon	70	Yb	ytterbium
19	K	potassium	71	Lu	lutetium
20	Ca	calcium	72	Hf	hafnium
21	Sc	scandium	73	Ta	tantalum
22	Ti	titanium	74	W	tungsten
23	V	vanadium	75	Re	rhenium
24	Cr	chromium	76	Os	osmium
25	Mn	manganese	77	Ir	iridium
26	Fe	iron	78	Pt	platinum
27	Co	cobalt	79	Au	gold
28	Ni	nickel	80	Hg	mercury
29	Cu	copper	81	Tl	thallium
30	Zn	zinc	82	Pb	lead
31	Ga	gallium	83	Bi	bismuth
32	Ge	germanium	84	Po	polonium
33	As	arsenic	85	At	astatine
34	Se	selenium	86	Rn	radon
35	Br	bromine	87	Fr	francium
36	Kr	krypton	88	Ra	radium
37	Rb	rubidium	89	Ac	actinium
38	Sr	strontium	90	Th	thorium
39	Y	yttrium	91	Pa	protactinium
40	Zr	zirconium	92	U	uranium
41	Nb	niobium	93	Np	neptunium
42	Mo	molybdenum	94	Pu	plutonium
43	Tc	technetium	95	Am	americium
44	Ru	ruthenium	96	Cm	curium
45	Rh	rhodium	97	Bk	berkelium
46	Pd	palladium	98	Cf	californium
47	Ag	silver	99	Es	einsteinium
48	Cd	cadmium	100	Fm	fermium
49	In	indium	101	Md	mendelevium
50	Sn	tin	102	No	nobelium
51	Sb	antimony	103	Lw	lawrencium

ATOMS

Atoms make up the fundamental building blocks of elements (such as oxygen and hydrogen). Elements differ from each other because they contain different kinds of atoms. In all elements, the atoms are the smallest individual particles of matter which cannot be subdivided without losing the identity of the particular element.

(There are approximately 6×10^{21} atoms in an ordinary drop of water.)

FUNDAMENTAL PARTICLES

An atom is composed of a small, dense, central region (called a nucleus) surrounded by electrons. A nucleus is basically composed of neutrons and protons. A neutron and a proton have approximately the same mass, while the mass of an electron has only about 1/1836 the mass of a proton. The diameter of a nucleus is on the order of 10^{-12} cm, whereas the diameter of an entire atom, including the electron cloud, is on the order of 10^{-8} cm. By comparison, if a nucleus were enlarged to the size of a baseball, the electrons would be nearly half a mile away. Obviously, the mass of an atom is concentrated mostly in the very small nucleus; nuclear density is about 10^{14} grams/cubic centimeter (g/cm^3) compared to only one g/cm^3 for water.

Neutrons have no electrical charge. Electrons have negative charges, and the protons have positive charges equal in magnitude to those of electrons. Atoms are normally electrically neutral; that is, the number of electrons surrounding the nucleus is equal to the number of protons in the nucleus.

An atom may be pictured as a planetary system of electrons in motion about a nucleus, somewhat analogous to the planets moving around the sun in our solar system. The electrons travel about the nucleus in well-defined orbits, or "shells."

In a two-dimensional illustration, an atom of zinc (Figure 1-3-1) has 30 electrons arranged in 4 shells.

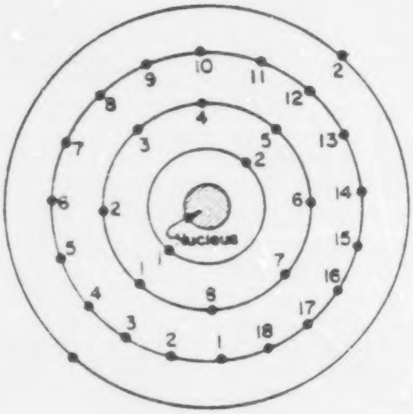

Figure 1-3-1.
The atomic structure of zinc
(nucleus greatly exaggerated).

MASS NUMBER AND ATOMIC NUMBER

The total number of protons plus neutrons in an atom is called its mass number, represented by the symbol A:

A = number of neutrons + number of protons.

Equation 1-3-1
(Equation = Eq.)

For example, consider the atoms illustrated in Figure 1-3-2:

	Hydrogen	Helium	Lithium	Beryllium
No. of protons =	1	2	3	4
No. of neutrons =	+0	+2	+4	+5
Mass numbers, A =	1	4	7	9

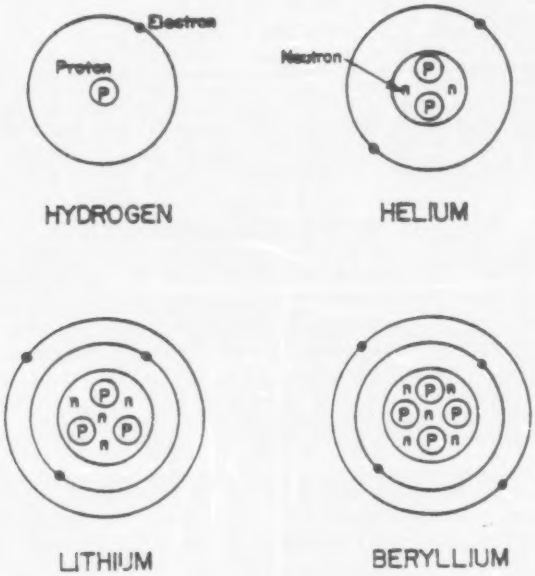
Electron
Proton
P
Neutron
n
HYDROGEN
HELIUM
LITHIUM
BERYLLIUM

Figure 1-3-2. Atoms of first four elements (nuclei greatly exaggerated).

The number of protons in an atom is its atomic number, represented by the symbol Z:

$$Z = \text{number of protons.}$$

$$\text{also, } A - Z = \text{number of neutrons.}$$

For example, again consider the atoms illustrated in Figure 1-3-2:

	Hydrogen	Helium	Lithium	Beryllium
No. of protons =	1	2	3	4
Atomic numbers, Z =	1	2	3	4

The electron structure of an atom (i.e., the arrangement of electrons in the orbits) primarily governs its chemical properties. In a neutral atom, the number of electrons and protons are equal, and its chemical behavior can be inferred from its unique atomic number. For example, hydrogen is the only element with an atomic number of one. Atomic numbers for all the elements are given in Table 1-3-1.

ISOTOPES

Any element (all the atoms of which contain the same number of protons) may occur with different numbers of neutrons. This means that an element can have atoms with a different atomic mass but with the same atomic number (hence same chemical properties). Such atoms are called isotopes of the element in question.

Hydrogen has three isotopes (Figure 1-3-3). Almost all hydrogen found in nature is composed of the ordinary hydrogen

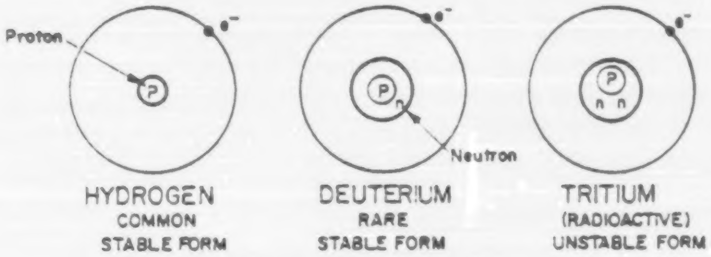
Proton
e⁻
P
e⁻
P
n
Neutron
e⁻
P
n n
HYDROGEN
COMMON
STABLE FORM
DEUTERIUM
RARE
STABLE FORM
TRITIUM
(RADIOACTIVE)
UNSTABLE FORM

Figure 1-3-3. Isotopes of hydrogen (nuclei greatly exaggerated).

isotope, which contains one proton and no neutrons in the nucleus. Hydrogen is the only element with an isotope that contains no neutrons. The nucleus of a "heavy" hydrogen (deuterium) atom contains a neutron as well as the usual proton. Heavy hydrogen atoms combine with oxygen to form "heavy" water. Only about 15 out of 1000 hydrogen atoms are heavy. (A still heavier hydrogen atom, tritium, has been artificially produced in nuclear reactors. It is radioactive.)

As a further illustration, helium has five isotopes (Figure 1-3-4). The isotope with two neutrons is commonly found in nature.

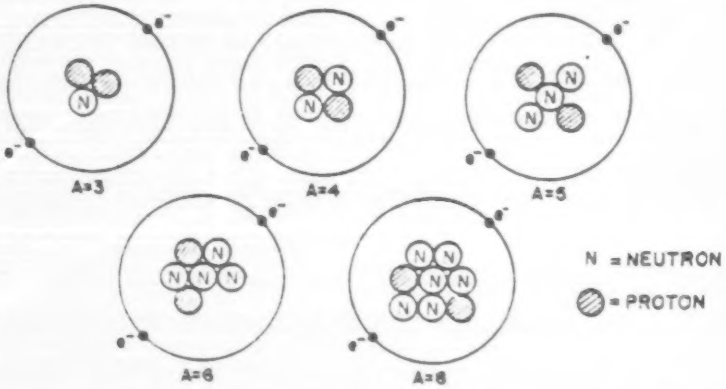

Figure 1-3-4. The five isotopes of helium.

The term isotope denotes the specific different forms of a single element: for example, atoms having the same atomic number but different mass number. The term nuclide denotes any species of atom, without reference to a particular element. The two terms (isotope and nuclide) are often used interchangeably, but isotope has a more limited definition. Also, the number of isotopes for each element varies. While hydrogen has three isotopes, helium has five and tin has 25.

In all, more than 1,500 different nuclides have been identified. About 900 are radioactive, which means they are unstable and will change in some way to attain a stable condition. There are 58 different naturally occurring radioactive nuclides, most of which belong to the heavier elements such as uranium and radium.

SYMBOLS

A method of symbolically identifying a nuclide (or an atomic structure) is ${}^{A}_{Z}X$, where X is the chemical symbol of the element, A is the mass number (number of neutrons plus protons) and Z is the atomic number (number of protons). Of course, A-Z always equals the number of neutrons. Symbols for typical nuclides are given in Table 1-3-2.

Frequently, a nuclide is represented without an atomic number, such as ${}^{A}X$ instead of ${}^{A}_{Z}X$. Such notation is essentially complete because once the chemical symbol is given, the atomic number (Z) is known and is, therefore, redundant. For example, the symbol ${}^{3}H$ represents an isotope of hydrogen that has an atomic number of 1 (thus ${}^{3}H = {}^{3}_{1}H$). The nuclide is also correctly represented in print by the chemical name or chemical symbol followed by the mass number, such as hydrogen-3 or H-3.

INTRODUCTION TO RADIOACTIVITY

Some isotopes of elements possess certain combinations of neutrons and protons, which causes the nucleus to be

TABLE 1-3-2

TYPICAL NUCLIDES

Number Symbol	Element	Atomic Number (Z)	Mass Number (A)	Number of Neutrons (A-Z)
${}^{1}_{1}H$	Hydrogen	1	1	0
${}^{2}_{1}H$	Hydrogen (Deuterium)	1	2	1
${}^{3}_{1}H$	Hydrogen (Tritium)	1	3	2
${}^{3}_{2}He$	Helium	2	3	1
${}^{4}_{2}He$	Helium (Alpha particle)	2	4	2
${}^{5}_{3}Li$	Lithium	3	5	2
${}^{6}_{3}Li$	Lithium	3	6	3
${}^{60}_{27}Co$	Cobalt	27	60	33
${}^{235}_{92}$	Uranium	92	235	143

unstable. This unstable condition results from an imbalance of forces in the nucleus. These unstable atoms are termed radioactive*. The nucleus of any given radionuclide will undergo a sudden, spontaneous decay or disintegration. This event will be accompanied by the release of energy and the emission of one or more types of radiation.

Until a radioactive atom disintegrates and emits radiation, there is no simple way to determine that it is radioactive, since a radioactive atom has the same number of protons in its nucleus as a nonradioactive atom of the same element. Therefore, it is chemically indistinguishable from the nonradioactive atom.

---

* Radioactive atoms are also called radionuclides.

A radioactive atom also has the same number of electrons as a nonradioactive atom of the same element. The difference between the two is found in the number of neutrons in the nucleus, which means only that their mass is different. And even this difference does not normally affect their chemical or biological behavior.

Thus, in general, radioactive atoms behave chemically and biologically like other atoms of the same element, which is what makes tracer experiments with radionuclides possible.

GM SCALER-COUNTER PLATEAU CURVE

Some radiation has the ability to ionize gas through which it passes; that is, the radiation removes electrons from the gas atoms to produce free electrons (negative ions) and positive ions. The Geiger-Mueller (GM) scaler-ratemeter uses this ionization process to measure radiation level by applying a voltage across the walls (negative) and central wire (positive) of the GM tube (Figure 1-3-5).

The sequence of processes that take place when a particle of ionizing radiation enters a GM tube is described as follows:

Some electrons are knocked out of several gaseous atoms within the tube.

These electrons, or negative ions, are immediately attracted toward the positive-charged central wire.

En route, these electrons are accelerated to a tremen-

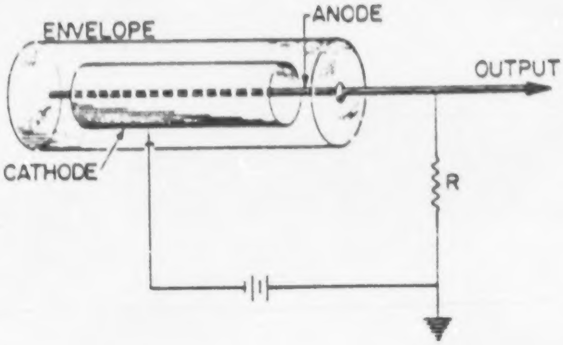

Figure 1-3-5.
Basic gas-filled detector.

dous speed by the electric field and collide with other gas atoms, thereby dislodging more electrons from the gas.

The dislodged electrons produce more ionization, and so on, causing an avalanche effect.

In all, more than a billion (10^9) electrons strike the central wire almost simultaneously.

A sharp pulse of current is formed as the electrons are collected by the wire.

This pulse is detected as a single count by the GM counter. (Individual pulses will be viewed on an oscilloscope as part of the laboratory exercise.)

The number of pulses or counts, detected by the GM scaler-ratemeter in a given counting period, depends on the voltage applied between the central wire and the cathode. A typical GM count rate versus voltage curve is shown in Figure 1-3-6. Such a curve is obtained to determine the instrument operating voltage.

Most GM scaler-ratemeters are designed so that pulses must be larger than a certain size to be counted. The voltage corresponding to this limiting pulse size is called

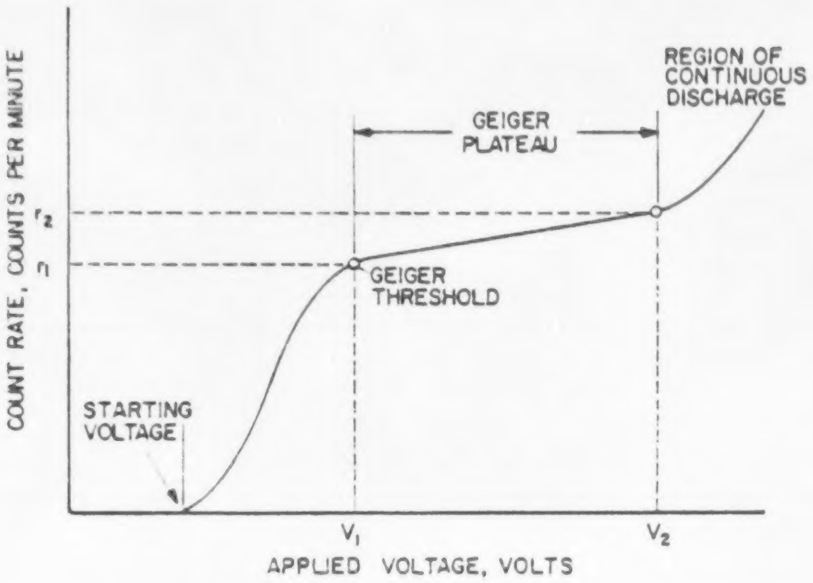

Figure 1-3-6. Typical curve for a Geiger-Mueller detector.

the starting voltage. As the voltage is increased above the starting voltage, a threshold voltage is reached, which signifies the beginning of the linear GM plateau. In the plateau range, the count rate varies only slightly with variations in applied voltage.

For normal operation of the GM counter, the voltage is set at some value on the plateau. The small variation in count rate with voltage over this range represents one of the most desirable features of the GM scaler-ratemeter: The power supply can be relatively inexpensive and lightweight because the voltages it supplies need not be maintained at an exact value (regulated). Small fluctuations in voltage cause no serious deviations in count rate readings.

Beyond the plateau, the tube may go into continuous discharge, which can cause damage to the tube. To ensure that a detector does not operate in this continuous discharge region, operating voltage should be set about 1/3 of the way along the plateau from the threshold voltage. Such a setting should be used for all subsequent exercises.

The length and slope of the plateau are two principal characteristics used to rate and compare GM tubes. Longer plateaus are better than shorter ones because of a decreased possibility of voltage variation affecting counting rate. For the same reason, tubes with smaller slopes in the plateau are preferred to those with larger ones.

A slope can be expressed as change in count rate, divided by any corresponding change in applied voltage (Figure 1-3-7).

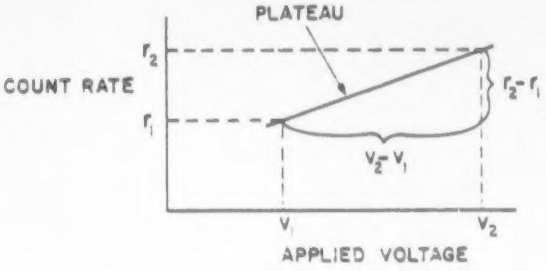

Figure 1-3-7.
Slope of count rate versus applied voltage.

The slope (S) may be expressed mathematically:

$$S = \frac{\text{change in count rate}}{\text{change in applied voltage}} \qquad \text{Eq. 1-3-2}$$

$$= \frac{r_2 - r_1}{v_2 - v_1}$$

where:

r_2, r_1 = count rates at end and beginning of plateau, respectively.

v_2, v_1 = applied voltages at end and beginning of plateau, respectively.

EXAMPLE

Given: A count rate of 3647 counts per minute (r_1) at 800 volts (v_1), and 4397 counts per minute (r_2) at 950 volts (v_2), calculate the slope.

Solution:

$$S = \frac{4397 \text{ cpm} - 3647 \text{ cpm}}{950 \text{ volts} - 800 \text{ volts}}$$

$$= \frac{750 \text{ cpm}}{150 \text{ volts}}$$

$$= 5.0 \text{ cpm/volt.}$$

A somewhat different measure related to the slope can also be expressed as the percentage increase in counting rate per 100 volts increase in the applied voltage:

$$S = \frac{\dfrac{r_2 - r_1}{r_1}}{\dfrac{v_2 - v_1}{100 \text{ volts}}} \times 100\% = \text{percent per 100 volts.}$$

EXAMPLE

Given: The counting rates and applied voltages from the previous example:

r_2 = 4397 cpm.
r_1 = 3647 cpm.
v_2 = 950 volts.
v_1 = 800 volts.

Calculate the slope in percent per 100 volts.

Solution:

$$S = \frac{\dfrac{r_2 - r_1}{r_1}}{\dfrac{v_2 - v_1}{100 \text{ volts}}} \times 100\%$$

$$= \frac{\dfrac{4397 \text{ cpm} - 3647 \text{ cpm}}{3647 \text{ cpm}}}{\dfrac{950 \text{ volts} - 800 \text{ volts}}{100 \text{ volts}}} \times 100\%$$

$$= \frac{0.2056}{1.5} \times 100$$

$$= 13.7\% \text{ per 100 volts.}$$

NET AND GROSS COUNTING RATES

The count rate taken with a radioactive source includes effects of both the radioactive source and natural background radiation. This count rate is called the "gross" or "total" counting rate.

It is usually desirable to determine the counting rate of only the radioactive source (the "net" counting rate). This rate is obtained by subtracting background counting rate from the gross counting rate:

$$\text{Net count rate} = \begin{array}{c}\text{total (or gross)}\\ \text{count rate}\end{array} - \begin{array}{c}\text{background}\\ \text{count rate}\end{array}$$

Eq. 1-3-4

EXAMPLE

Given: A Co-60 sample in which 8000 total counts were collected during a 2-minute period. Without the source present, background radiation was found to be 1000 counts collected during a 10-minute period. Find net counting rate.

Solution:

Total count rate

$$= \frac{8000\ \text{counts}}{2\ \text{minutes}}$$

= 4000 counts per minute (cpm).

Background count rate

$$= \frac{1000\ \text{counts}}{10\ \text{minutes}}$$

= 100 cpm.

Net count rate

= 4000 cpm - 100 cpm

= 3900 cpm.

EXERCISES

1. In deciding the level at which to set the high-voltage supply of a counting system, it is necessary to find the point in the voltage range where the change in counts per minute for a given change in voltage is minimum.

   Given a voltage range of 200-1000 volts and counts for each voltage as follows:

   200 volts - 800 cpm.
   300 volts - 1450 cpm.
   400 volts - 1800 cpm.
   500 volts - 2200 cpm.
   600 volts - 2200 cpm.
   700 volts - 2300 cpm.
   800 volts - 2500 cpm.
   1000 volts - 4000 cpm.

   Locate and indicate the 100-volt range in which the change in counts per minute is minimum.

2. If an employee counts a sample of a potentially radioactive substance for 2 minutes and the total count is 2200, what is the count rate per minute? If the background count rate is 100 counts per minute, what is the net count rate from the sample?

MATERIALS

1 Radioactive source*.
1 Geiger-Mueller end-window probe*.
1 Geiger-Mueller scaler-ratemeter*.
1 Timer*.
1 Sample holder*.
1 Oscilloscope.
Graph paper - linear.

---

* Per group of two or three students.

PROCEDURES

GEIGER-MUELLER PLATEAU

1. Turn the Geiger-Mueller scaler-ratemeter to "on" and wait for it to warm up.
2. Place radioactive source on shelf of sample holder; place end-window GM probe on top of sample holder.
3. Record information asked for on Data Table 1-3-1.
4. Turn high-voltage switch to minimum setting.
5. Adjust high-voltage setting until counting begins (at about 700-900 volts).
6. Take one-minute count at starting voltage.
7. Record voltage and count rate on Data Table.
8. Increase starting voltage by 25 volts; repeat counting; record data.

9. Repeat the previous procedure (increasing voltage each time) until voltage reaches a value specified by instructor (or operating manual), or until the region of continuous discharge is approached.
   CAUTION: Do not exceed this voltage: tube could be damaged.
10. Plot a count-rate versus applied-voltage curve on linear graph paper. Be sure to properly title the curve and label both axes of the graph.
11. Identify starting voltage, threshold voltage, plateau range and region of continuous discharge on the graph. Write these values on the Data Table.
12. Calculate an appropriate operating voltage on the Data Table; indicate its value on the graph.
13. Calculate the range and slopes on the Data Table; use equations shown in the text.

PULSE DEMONSTRATION ON OSCILLOSCOPE

The instructor will connect oscilloscope leads to the GM scaler-ratemeter output terminals and adjust controls of oscilloscope according to the operating manual to demonstrate the pulse character of GM counter system. Sketch this pulse. On the sketch, label 1) maximum output voltage, 2) pulse width and 3) duration of pulse.

DATA TABLE

DATA TABLE 1-3-1

A. DATA:

Lab partners in group ____________________.

Date ____________________.

Radioactive source used ____________________.

Scaler-counter used ____________________.

Geiger-Mueller tube used ____________________.

Shelf position in sample holder ____________________.

Time interval for counts ____________________.

Time	Voltage, Volts	Counts	Count Rate (cpm)

B. VALUES FROM GRAPH:

Starting voltage __________ = v_0 (Figure 1-3-6).

Threshold voltage __________ = v_1 (Figure 1-3-6).

Threshold count rate __________ = r_1 (Figure 1-3-6).

End of plateau voltage __________ = v_2 (Figure 1-3-6).

End of plateau count rate __________ = r_2 (Figure 1-3-6).

C. CALCULATIONS:

1. Operating voltage = $v_1 + 1/3\ (v_2 - v_1)$

$$= (\underline{\qquad\qquad}) + 1/3\ (\underline{\qquad} - \underline{\qquad})$$

$$= \underline{\qquad\qquad} \text{ volts.}$$

2. Range = $v_2 - v_1 = (\underline{\qquad\qquad}) - (\underline{\qquad\qquad})$

$$= \underline{\qquad\qquad} \text{ volts.}$$

3. Slope (cpm/volts) = $\dfrac{r_2 - r_1}{v_2 - v_1} = \dfrac{(\underline{\qquad\quad}) - (\underline{\qquad\quad})}{(\underline{\qquad\quad}) - (\underline{\qquad\quad})}$

$$= \underline{\qquad\qquad} \text{ cpm/volts.}$$

4. Slope (% per 100 volt) = $\dfrac{\dfrac{r_2 - r_1}{r_1}}{\dfrac{v_2 - v_1}{100 \text{ volts}}} \times 100\%$

$$\frac{\dfrac{(\qquad) - (\qquad)}{(\qquad)}}{\dfrac{(\qquad) - (\qquad)}{100 \text{ volts}}} \times 100\% = \underline{\qquad\qquad} \text{ \% per 100 volts}$$

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TEST

Circle the letter of the best response to each definition or statement 1-6.

1. The smallest individual particle of matter which cannot be subdivided without losing the identity of the particular element.

   a. neutron
   b. electron
   c. atom
   d. element

2. A fundamental substance which cannot be changed into another fundamental substance by ordinary chemical or physical processes.

   a. atom
   b. element
   c. proton
   d. atomic mass

3. Those atoms which have the same atomic number but different mass numbers.

   a. isotopes
   b. ions
   c. elements
   d. electrons

4. Any species of atom without reference to a particular element.

   a. isotope
   b. nuclide
   c. heavy hydrogen atom
   d. mass number

5. Select the statement which is most descriptive of an atom.

   a. The nucleus contains most of the mass but occupies the least volume.
   b. The nucleus contains the least mass but occupies the most volume.
   c. The number of electrons equals the number of neutrons.
   d. The heaviest particle is the electron.

6. Select the statement that gives the advantage of a G-M counter in terms of operating voltages.

   a. A small voltage change results in a large change to count rate.
   b. The G-M requires less than 100 volts to operate.
   c. Each radiation event causing arcing of the G-M tube.
   d. An unregulated, portable power supply can be used.

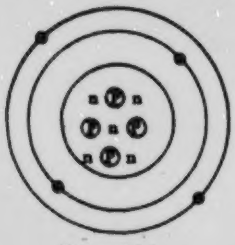
7. Fill in the appropriate spaces on the chart below. Indicate the following: The names of the three fundamental particles of the atom, the location of each particle with respect to the nucleus, the electrical charge of each particle.

NAME OF PARTICLE	LOCATION	ELECTRICAL CHARGE
1.		
2.		
3.		

8. Below are symbolic notations for five atoms. For each atom list the name of the element and the element's atomic number.

SYMBOL	NAME OF ELEMENT	ATOMIC NUMBER
He		
C		
O		
H		
N		

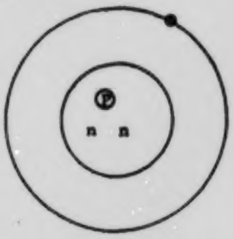
9. Below are simplified drawings of the atoms for three elements. For each atom, write the atomic number and the mass number.



Beryllium

A = ______

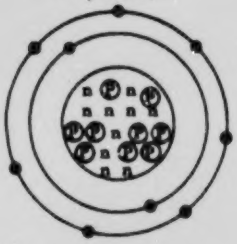
Z = ______



Tritium

A = ______

Z = ______



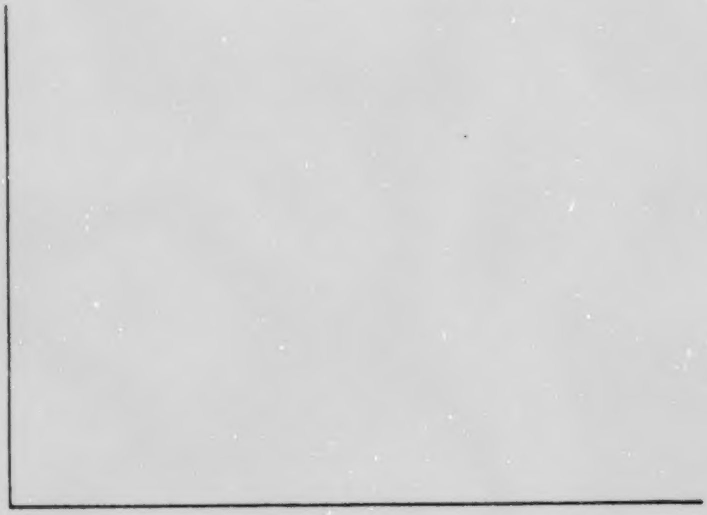
Fluorine

A = ______

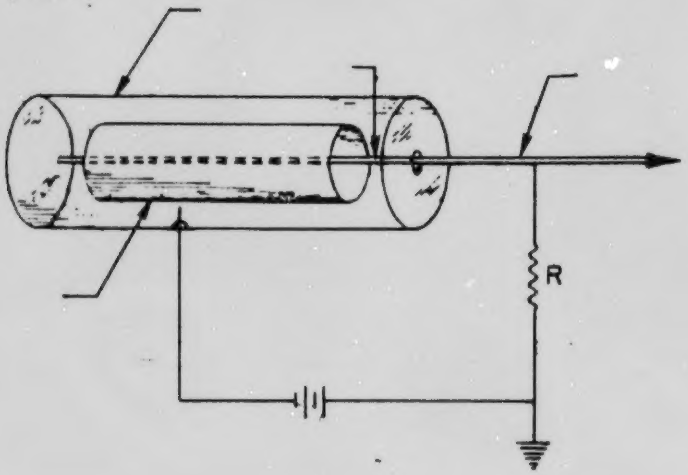
Z = ______

10. The element uranium 238 has an atomic number of 92. How many protons does uranium have? ____________________ How many neutrons does uranium have? ________________ What is the mass number of uranium? ________________

11. Using the axes below, draw a typical G-M count rate vs. voltage curve. Identify: the axes, G-M plateau, starting voltage, threshold and region of continuous discharge.



12. Lable the parts of the G-M (Geiger-Mueller) tube to which the arrows point:



13. Given below are the sequence of processes that take place when a particle of ionizing radiation enters a G-M tube. Number the processes in the order in which they occur. 1 - 6.

a. ______ sharp pulse of current is formed as electrons are collected by the central wire

b. ______ electrons accelerate and collide with other gas atoms dislodging more atoms from the gas

c. ______ electrons or negative ions are attracted toward positive-charged central wire

d. ______ pulse is detected as a single count by the G-M counter

e. ______ electrons are knocked out of several gaseous atoms within the tube

f. ______ dislodged electrons produce more ionization, causing an avalance effect as electrons simultaneously strike central wire

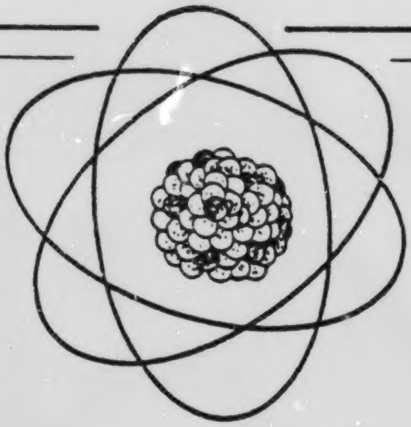
14. When the voltage of the Geiger-Mueller detector is increased beyond the plateau, the tube may go into continuous discharge. Would you want the tube to operate in the continuous discharge region? Why?

---

15. Very briefly, how would you go about determining background count rate in the laboratory?

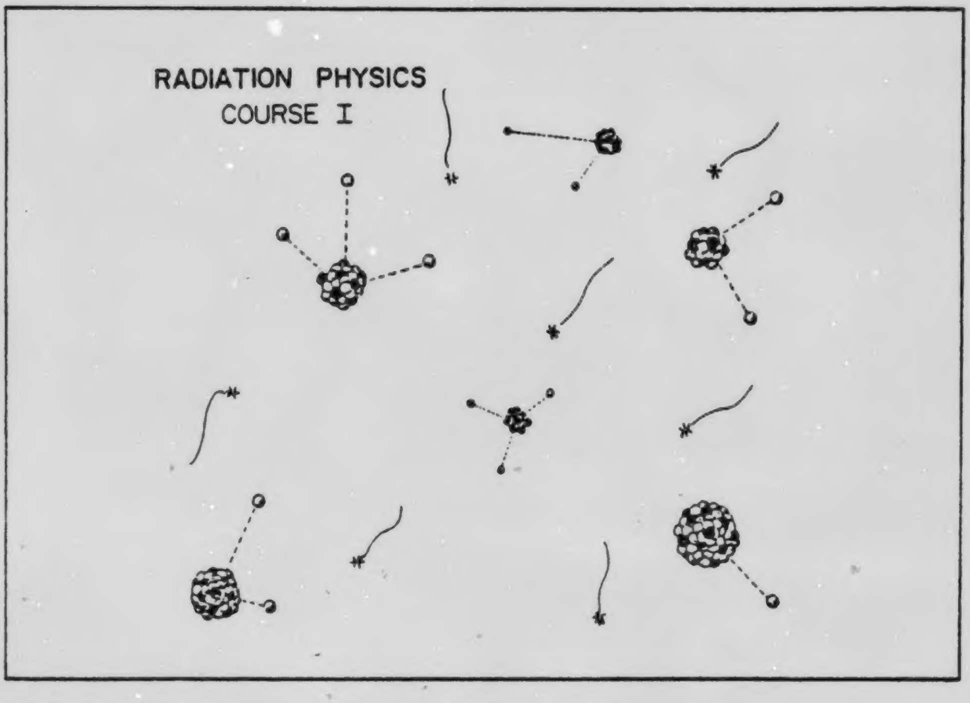
____

16. Given a background count rate of 50 counts per minute and a gross count rate of 6,000 counts during a two minute interval, calculate the net count rate per minute.



NUCLEAR TECHNOLOGY

MODULE 1-4 RADIOACTIVE DECAY AND HALF-LIFE



RADIATION PHYSICS
COURSE I

COURSE MODULES

COURSE 1 RADIATION PHYSICS

	MODULE 1-1	Introduction to Radiation Laboratory Safety
	MODULE 1-2	Basic Radiation Detection and Measuring Equipment
	MODULE 1-3	Atomic Structure and Radioactivity
⇨	MODULE 1-4	Radioactive Decay and Half-life
	MODULE 1-5	Decay Processes and Schemes
	MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Radioactive decay is the spontaneous disintegration or transformation of one nuclide into another. Nuclides that undergo such decay are said to be "radioactive" or unstable, and nuclides that do not undergo this decay are said to be "nonradioactive" or stable.

Radioactive atoms are atoms of certain nuclides in which the forces that act on the nuclei are not properly balanced. The principal forces are, first, repelling electrostatic forces (forces that repel positive-charged protons away from one another) and, second, attracting nuclear forces (forces that pull protons and neutrons toward one another). Whether a certain nuclide is stable or unstable depends on its combination of nucleons (protons and neutrons). Some combinations are highly unstable while others are relatively stable.

Radioactive decay results in a decrease, with time, from the original number of radioactive atoms in a sample, and radioactive nuclides that undergo decay are usually changed into a different type of nuclide. It is not possible to say exactly when a particular radioactive atom will decay, because the decay process is random; however, the total number of radioactive atoms present in any sample undergoes a predictable, continuous change. The number of atoms undergoing decay within any specified time period and the amount of radioactivity can be calculated with reasonable accuracy.

An important property of a radioactive nuclide is its half-life - that period of time in which half the atoms of a particular radioactive nuclide (called the "parent") decay to another nuclide (called the "daughter"). Each radioactive nuclide has its own characteristic half-life, which does not change with time or size of sample. Measured half-lives vary from less than millionths of a second to billions of years.

The purpose of this module is to acquaint the student with radioactive decay, the concept of half-life, and methods of calculating the amounts of radioactivity and radioactive decay.

MODULE PREREQUISITES

The student should have successfully completed Modules 1, 2 and 3 of this Course, and be able to perform mathematical functions with logarithms and exponentials.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define and/or cite an example of each of the following:
    Radioactive decay.
    Stability.
    Nuclear force.
    Electrostatic force.

- Half-life.
- Decay constant.
- Activity.
- Specific activity.
- Avogadro's number.
- Curie.
- Nucleon.
- Gram-atomic weight.
- Atomic weight.

2. Given the general exponential relationship for radioactive decay, discuss the relation between decay constant and half-life.
3. Use an appropriate GM scaler-ratemeter and a short-lived radionuclide with a stable daughter to perform the following tasks:
    - Count the sample over a period of several half-lives and plot the results on a graph of activity versus time.
    - Use the above plotted data to determine decay constant and half-life; use the exponential relationship.
    - Identify and demonstrate sources of variation between predicted and measured values of half-life.
4. Calculate the following values (include appropriate equations, conversion factors and units):
    - Fraction of radioactive material that decays in a specified time, given the half-life or radionuclide.
    - Number of atoms present in a sample of known mass and atomic weight.
    - Activity (disintegrations per second and Curies)

of a radioactive sample of known mass, atomic weight and half-life.

Specific activity of a radioactive sample of known mass and activity.

NUCLEAR FORCES AND STABILITY

The protons and neutrons (both also called nucleons) within the nucleus are acted upon by two sets of forces, electrostatic and nuclear (Figure 1-4-1). Electrostatic (or Coulombic) forces act on positively-charged protons to force them apart (like charges repel one another). Nuclear forces act on all nucleons (protons and neutrons) to pull them together. Nuclear forces, which are extremely strong and always attract, are the same for neutrons and protons but are zero for electrons. These forces, though much stronger than gravitational forces, only act over very short distances (on the order of nuclear diameters).

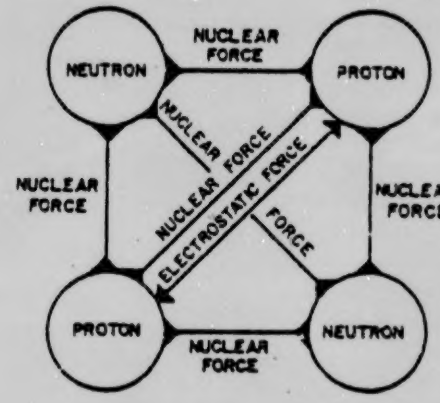

NEUTRON
NUCLEAR FORCE
PROTON
NUCLEAR FORCE
NUCLEAR FORCE
NUCLEAR FORCE
ELECTROSTATIC FORCE
FORCE
NUCLEAR FORCE
NUCLEAR FORCE
PROTON
NEUTRON
NUCLEAR FORCE

Figure 1-4-1.
Electrostatic and nuclear forces acting on neutrons and protons. ^{4}He given as example.

The combined effects of the electrostatic (repelling) and nuclear forces (attracting) are such that only certain combinations of neutrons and protons are stable (i.e., resist decay or fission). In general, combinations which contain fewer protons are more unstable. Because of its complex nature, nuclear stability is determined by many factors; however, a discussion of such factors is beyond the scope of this module and is usually considered only in upper level nuclear physics courses.

DECAY RATE

A radioactive nucleus may decay at any time after its formation. It has been found that this process is completely random, so that the behavior of only a large number of radioactive nuclei can be described by the laws of probability or statistics. The probability of decay of an atom in a particular time period is independent of the age of its nucleus, independent of the atom's surroundings and is the same for all nuclei of that specific type. This probability of decay per nucleus in unit time is called the decay constant (λ) for that type of nucleus.

Assume a radioactive source and some means of counting the number of atoms that disintegrate in a given time interval. If the number of atoms present is plotted at a given time versus a progression of the time on linear graph paper (Figure 1-4-2), the curve obtained indicates an exponential or logarithmic relationship. If the number of original atoms remaining versus time is plotted on semilog paper (Figure 1-4-3), a straight line is obtained, which indicates that radioactive decay is an exponential (logarithmic) process;

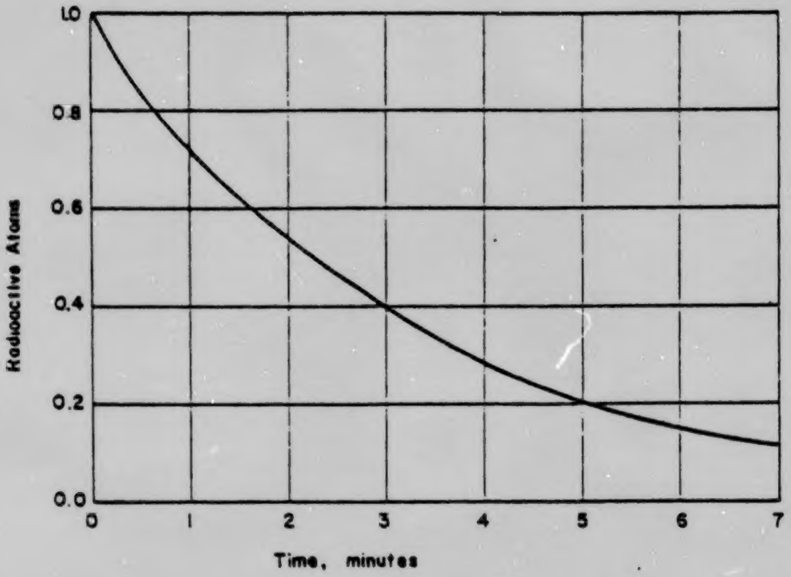


Figure 1-4-2. Fraction of radioactive atoms present at a given time versus time (example only).

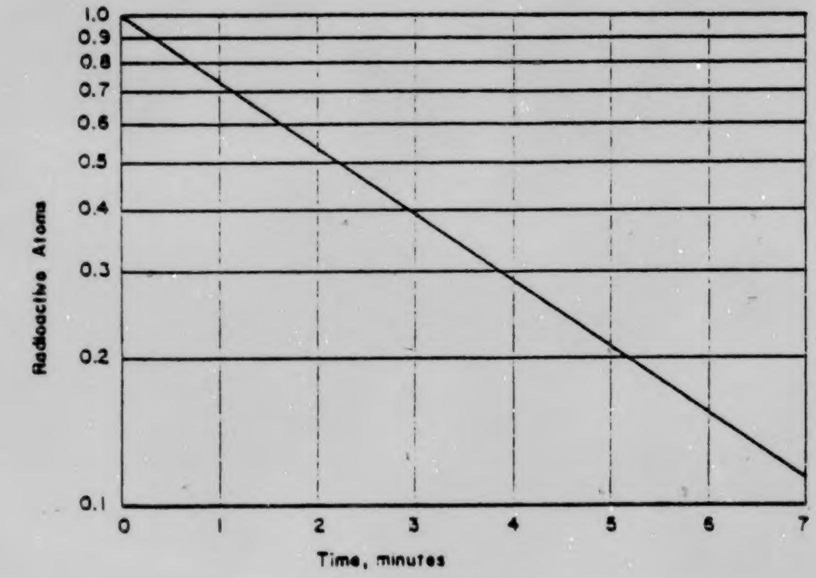


Figure 1-4-3. Fraction of radioactive atoms at a given time versus time (example only).

that is, a constant fractional decrease in decay rate occurs during equal units of time.

Although the same number of atoms do not disintegrate during each unit of time, the same fraction does. This fact leads to the general exponential relationship for radioactive decay:

$$N = N_o e^{-\lambda t}$$ Equation 1-4-1
(Equation = Eq.)

where:

N = number of atoms left at time t from a sample of N_o radioactive atoms initially present at time $t = o$.

e = the exponential function ($e = 2.71828$).

λ = decay constant (in units of 1/time).

EXAMPLE

Given: A time progression of 4.0 hours; a radioactive sample now containing 10^{22} atoms; a decay constant of 0.1 hr^{-1}. That is,

$\lambda = 0.1\ hr^{-1}$.
$N_o = 10^{22}$ atoms.
$t = 4.0$ hr.

FIND: N.

SOLUTION:
$$N = N_o e^{-\lambda t}$$
$$= (10^{22} \text{ atoms})$$
$$(e^{-0.1\ hr^{-1} \times 4.0\ hr})$$

$$= (10^{22}\text{ atoms})\ (e^{-0.4})^{*}$$
$$= 0.67 \times 10^{22}\text{ atoms}$$
$$N = 6.7 \times 10^{21}\text{ atoms.}$$

---

* $(e^{-0.4}) = 0.67$

It is often desirable to determine the decay constant, given the number of atoms at two different times. To do so, take the natural logarithm of each side of Equation 1-4-1:

$$N = N_o e^{-\lambda t}$$
$$\ell n\ (N) = \ell n\ (N_o e^{-\lambda t})$$
$$\ell n\ (N) = \ell n\ (N_o) + \ell n\ (e^{-\lambda t})$$
$$\ell n\ (N) = \ell n\ (N_o) - \lambda t$$

where the mathematical identities below are frequently employed:

$$\ell n\ (xy) = \ell n\ x + \ell n\ y$$

and $\ell n\ e^{x} = x$

(x and y are any unknown variables).

To solve the equation for λ:

$$\lambda = \frac{\ell n\ (N_o) - \ell n\ (N)}{t} = \frac{\ell n\ (N_o/N)}{t}\ . \qquad \text{Eq. 1-4-2}$$

This equation is used to derive a decay constant λ from experimental data.

EXAMPLE

Plot the following data on three-cycle* semilog paper and determine the decay constant λ:

Time, Seconds	Number of Atoms
0	9500×10^{20}
5	4000×10^{20}
10	1500×10^{20}
15	600×10^{20}
20	270×10^{20}
25	100×10^{20}
30	42×10^{20}

Plot number of atoms on logarithmic scale, and corresponding value of time on linear scale (Figure 1-4-4). Note: Plot is a straight line.

The decay constant λ may be obtained as follows (from Equation 1-4-2):

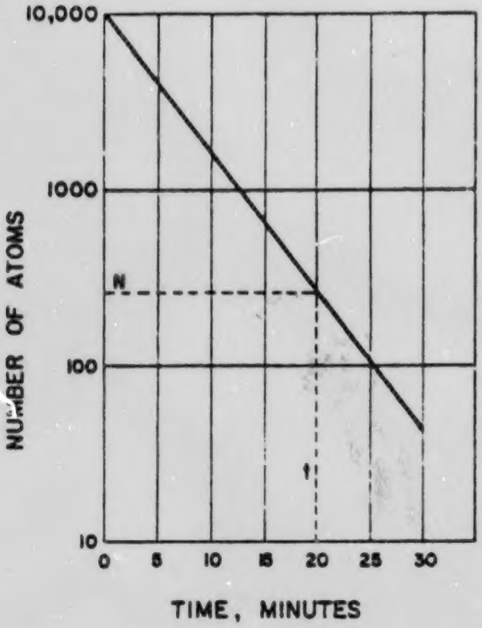
$$\lambda = \frac{\ln (N_0/N)}{t} .$$

The number of atoms initially is N_0 (= 9500 x 9500 x 10^{20}) and the number of atoms at any time,

---

* Three-cycle means that graph covers three powers of 10. In this case, the graph covers the ranges 10-100; 100-1000, and 1000-10,000.

Figure 1-4-4
Radioactive decay curve - example only.



t, is N. From the graph, time (t) was aribtrarily chosen as 20 seconds and the corresponding number of atoms is 260×10^{20}. (Note: Choose a value of N from the straight line and not from actual data, which may contain experimental errors.)

Equation 1-4-2 can be written as follows:

$$\lambda = \frac{\ln (9500 \times 10^{20} \text{ atoms})/(260 \times 10^{20}) \text{ atoms}}{20 \text{ seconds}}$$

where:

$N_o = 9500 \times 10^{20}$ atoms.
$N = 260 \times 10^{20}$ atoms.
$t = 20$ sec.

Thus,

$$\lambda = \frac{\ln (36.54)}{20 \text{ sec}} = \frac{3.598}{20 \text{ sec}} = \frac{0.180}{\text{sec}}$$

$$= 0.180 \text{ sec}^{-1}$$

$$= 18 \times 10^{-2} \text{ sec}^{-1} \text{ or } 180 \text{ msec.}$$

Note that the unit is reciprocal time.

The decay constant expresses the probability that an atom will decay in a unit of time. The larger the value of λ, the more rapidly a radionuclide may decay.

ACTIVITY

The decay rate of a given sample, rather than the number of atoms present, is usually the measure of interest. This activity (A) of a sample is expressed as:

$$A = \frac{\Delta N}{\Delta t} = \lambda N \qquad \text{Eq. 1-4-3}$$

$$A = \lambda N.$$

In other words, activity of a sample can be found by multiplying N (the number of atoms present at any one time) by the decay constant (λ) of the radionuclide. The activity is the number of atomic nuclei decaying during any time period.

Activity is expressed in units of counts per unit time, or disintegrations per unit time.

EXAMPLE

Given: At an instant of time (t), a radioactive sample contains 10^{18} atoms and has a decay constant of 10^{-7} sec^{-1}.

Find the activity in disintegrations per second.

Solution:

$$A = \lambda N$$

$$A = 10^{-7} \text{ sec}^{-1} \times 10^{18} \text{ atoms}$$

$$A = 10^{11} \text{ atoms disintegrating/sec.}$$

Thus, the activity is 10^{11} disintegration per second (dis/sec or dps).

Now an equation for activity as a function of time can be derived as follows from Equation 1-4-1:

$$N = N_o e^{-\lambda t}.$$

Multiply both sides by λ:

$$\lambda N = \lambda N_o e^{-\lambda t}.$$

If $A = \lambda N$ and $A_o = \lambda N_o$, then

$$A = A_o e^{-\lambda t} \qquad \text{Eq. 1-4-4}$$

where:

A = activity of the sample at any time, t.
A_o = activity (decay rate) of the sample at t = o.

Equation 1-4-4 can be solved for λ as follows:

$$\lambda = \frac{\ell n \, (A_o/A)}{t} \, . \qquad \text{Eq. 1-4-5}$$

Note that Equation 1-4-2 and Equation 1-4-5 have the same form, and both can be used to determine λ.

EXAMPLE

Given: A radioactive sample, with a decay constant (λ) of 0.3 day^{-1}, is decaying presently at the rate (A) of 10^9 dis/sec.

Find the activity (decay rate) for seven days ago.

(Note: The activity that occurred first is designated A_o and that which occurs later is designated A.)

Solution:

$$A = A_o e^{-\lambda t}.$$

Rearranged:

$$A_o = \frac{A}{e^{-\lambda t}} = \frac{10^9 \text{ dis/sec}}{e^{-0.3 \text{ day}^{-1} \times 7.0 \text{ day}}}$$

$$A_o = \frac{10^9 \text{ dis/sec}}{(e^{-2.1})^*}$$

$$A_o = \frac{10^9 \text{ dis/sec}}{0.1225}$$

$$A_o = 8.16 \times 10^9 \text{ dis/sec at } t_o.$$

Thus, seven days ago, the sample, which is now decaying at a rate of 10^9 dps, was decaying at a rate of 8.17×10^9 dps, or essentially eight times as fast.

---

* $(e^{-2.1}) = 0.1225$

HALF-LIFE

The emission of radiation is a purely random process; that is, the particular atom that will next disintegrate or emit radiation is not known. But for very large numbers of atoms, it is possible to associate a definite time in which half this number of atoms will disintegrate. This time is called the half-life. (Compare this situation with the vital statistics of an insurance company: It cannot be said which individual will die in a given year, but, in a very large group, it can be predicted how many will die per year.)

The half-life of a radioactive substance is a characteristic time for a given isotope of an element. Among the many natural radioactive substances, half-lives are found ranging from a small fraction of a second to billions of years. Radium-226 has a half-life of about 1600 years. This means that, if there is 1 gram now, there will be 1/2 gram in about 1600 years, 1/4 gram in 3200 years, etc., so that, in each 1600 years, the number of radium-226 atoms is halved (Figure 1-4-5).

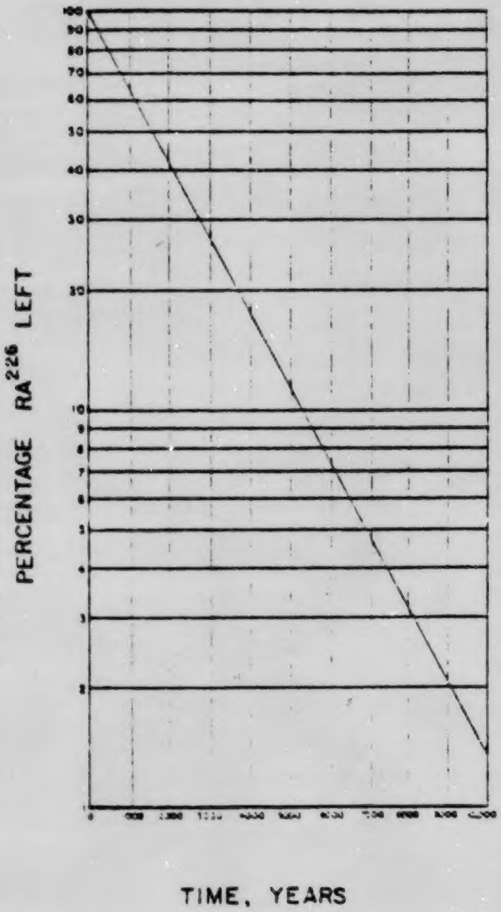


Figure 1-4-5.
Decay curve for ^{226}Ra
(half-life - 1600 years).

With the exception of certain nuclides, which are discussed later, no means is known by which the half-life of a substance can be changed. It is unaffected by time, temperature, pressure or chemical reaction.

Decay constant (λ) is closely related to the concept of half-life of a radionuclide. Half-life ($T_{\frac{1}{2}}$) is defined as the time required for a given nuclide to decay to one-half of its initial value. Consider an initial activity, A_o. At some time $t = T_{\frac{1}{2}}$, the activity will be equal to $A_o/2$. From the general relationship (Equation 1-4-4),

$$A = A_o e^{-\lambda t}.$$

After one half-life, $t = T_{\frac{1}{2}}$, $A = \frac{A_o}{2}$ so that

$$\tfrac{1}{2}A_o = A_o e^{-\lambda T_{\frac{1}{2}}}$$

$$\tfrac{1}{2} = e^{-\lambda T_{\frac{1}{2}}}.$$

Then, by taking natural logs of both sides,

$$\ln 1 - \ln 2 = -\lambda T_{\frac{1}{2}}$$

since $\ln 1 = 0.$

$\ln 2 = 0.693.$

$0.693 = \lambda T_{\frac{1}{2}}.$

By rearranging and solving for $T_{\frac{1}{2}}$,

$$T_{1/2} = \frac{0.693}{\lambda} .$$

and

$$\lambda = \frac{0.693}{T_{1/2}} . \qquad \text{Eq. 1-4-6}$$

Measured half-lives range from about 10^{-14} years (^{212}Po) to about 10^{17} years (^{209}Bi), giving a ratio of longest to shortest of 10^{31}. The extremely short and extremely long half-lives can be determined by more elaborate means than slope-of-activity versus time-curve.

ATOMIC WEIGHT AND GRAM-ATOMIC WEIGHT

The atomic weight of an individual neutral atom is the weight or mass* of that atom. This number is very small, on the order of 10^{-24} to 10^{-22} grams. Since the numbers are very small and inconvenient to work with, a special unit of mass, called the atomic mass unit (AMU), is used. The AMU is defined as 1/12 the mass of a neutral carbon-12 atom.

Atomic weight (expressed in AMU's) is approximately equal to the mass number. The atomic weight and mass numbers of typical nuclides are given in Table 1-4-1. Note that the mass number is the nearest whole number to the atomic weight in AMU's.

---

* Weight and mass are considered to be numerically identical here.

TABLE 1-4-1

Nuclide	Mass Number	Atomic Weight (in AMU's)
H-2	2	2.01410
Li-6	6	6.01512
Be-9	9	9.01219
C-12	12	12.00000
N-14	14	14.00307
U-235	235	235.04380

Another useful quantity is the gram-atomic weight (g-at.wt), which is the weight in grams of 6.02×10^{23}* atoms of any nuclide. It is numerically equal to atomic weight in AMU's. Typical examples are shown in Table 1-4-2. Thus, the atomic weight and the gram-atomic weight are equal numerically but have different units. The atomic weight is the weight of one atom measured in AMU, and the gram-atomic weight is the weight of 6.02×10^{23} atoms measured in grams. (Gram-atomic weight is often called gram-atom for convenience.)

TABLE 1-4-2

Nuclide	Atomic Weight (1 Atom)	Gram-Atomic Weight (6.02×10^{23} Atoms)
H-2	2.01410 AMU's	2.01410 grams
C-12	12.00000 AMU's	12.00000 grams
U-235	235.04380 AMU's	235.04380 grams

---

* This number (6.02×10^{23}) is known as Avogadro's number.

AVOGADRO'S NUMBER

Avogadro's number is the number of atoms present in one gram-atom (or gram-atomic weight) of a nuclide. This number is 6.02×10^{23} atoms/gram-atom. The number of atoms (N) in a sample may be shown as follows:

$$N = \frac{N_a M}{\text{g-at.wt}} \qquad \text{Eq. 1-4-7}$$

where:

N_a = Avogadro's number.
M = mass of sample, grams.

The number of atoms present in one gram-atomic weight is, therefore, a constant, no matter what the nuclide.

EXAMPLE

Given: A one-pound (454-gram) sample of natural aluminum (composed entirely of ^{27}Al, which has a gram-atomic weight of 26.98154 grams).

Find the number (N) of atoms present.

Solution:

$$N = \frac{N_a M}{\text{g-at.wt}}$$

$$N = \frac{6.02 \times 10^{23} \ \frac{\text{atoms}}{\text{gram-atom}} \times 454 \text{ grams}}{26.98154 \text{ grams/gram-atom}}$$

$N = 1.013 \times 10^{25}$ atoms

Note: All units except atoms cancel out.

CURIE: UNIT OF RADIOACTIVITY

The activity of a radioactive sample is often expressed in terms of Curies. One Curie is defined as the decay of 3.7×10^{10} nuclei/second, which corresponds approximately to the activity of 1 gram of radium without daughter products. Smaller units are the millicurie (1 mCi - 10^{-3} Ci) and the microcurie (1 μCi = 10^{-6} Ci); larger units are the kilocurie (1 kCi = 10^{3} Ci) and the megacurie (1 MCi = 10^{6} Ci).

Activities of laboratory radionuclides are usually in the microcurie range, and activities on the order of megacuries are not unusual for fuel elements, especially immediately after removal from a reactor.

It was shown in the section on activity that a specimen containing N atoms (or nuclei) of a given radioisotope decays at the rate λN:

$$A = \lambda N \text{ (dis/sec)}$$

where:

λ = decay constant, 1/sec.

N = number of radioactive atoms.

This activity also can be expressed in Curies (one Curie equals 3.7×10^{10} disintegrations/sec):

$$A \text{ (in Curies)} = \frac{A \text{ (in dis/sec)}}{3.7 \times 10^{10} \text{ dis/sec/Curie}}$$

$$A \text{ (in Curies)} = \frac{\lambda N \text{ (dis/sec)}}{3.7 \times 10^{10} \text{ dis/sec/Curie}}$$

Eq. 1-4-8

By substituting Equation 1-4-7 into Equation 1-4-8, A may be determined as follows:

$$A \text{ (in Curies)} = \left(\frac{\lambda}{3.7 \times 10^{10} \text{ dis/sec/Curie}}\right)\left(\frac{N_a M}{\text{g-at.wt}}\right)$$

Eq. 1-4-9

The activity of a given radionuclide depends on its mass, atomic weight and decay constant or half-life.

EXAMPLE

Given: A 0.1-microgram sample of Cs-137 (a common laboratory radionuclide, which has a half-life of 30.2 years and an atomic weight of 136.951 AMU.

Find activity in Curies and microcuries.

Solution: Use Equation 1-4-6 to determine the decay constant (λ):

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{30.2 \text{ years}} = 0.0229 \text{ year}^{-1}.$$

Convert the time from years to seconds (because Curies are defined in terms of dis/sec).

$$\lambda = \frac{0.0229}{\text{yrs}} \times \frac{1 \text{ yr}}{365 \text{ days}} \times \frac{1 \text{ day}}{24 \text{ hrs}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}}$$

$$\lambda = \frac{0.0229}{3.15 \times 10^{7} \text{ seconds}} = 7.27 \times 10^{-10} \text{ sec}^{-1}.$$

Now, substitute in Equation 1-4-8:

$$A \text{ (in Curies)} = \frac{\lambda}{3.7 \times 10^{10}} \frac{N_a M}{\text{g-at.wt}}$$

$$= \left(\frac{7.27 \times 10^{-10} \text{ sec}^{-1}}{3.7 \times 10^{10} \text{ dis/sec/Curie}}\right)$$

$$\left(\frac{6.02 \times 10^{23} \text{ atoms/gram-atom} \times 0.1 \times 10^{-6} \text{ grams}}{136.951 \text{ grams/gram-atom}}\right)$$

$$A = \frac{7.27 \times 10^{-10} \times 6.02 \times 10^{23} \times 0.1 \times 10^{-6} \text{ Curies}}{3.7 \times 10^{10} \times 136.951}$$

$$A = 8.637 \times 10^{-6} \text{ Curies.}$$

Now, since 1 microcurie = 10^{-6} Curies:

$$A = 8.637 \times 10^{-6} \text{ Curie} \times \frac{1 \text{ microcurie}}{10^{-6} \text{ Curie}}$$

$$A = 8.637 \text{ microcuries.}$$

Module 1-5, "Radioactive Decay Processes and Schemes," explains why the number of emitted particles need not be identical with the number of decay processes. If a certain radioisotope emits a single particle per atom, then rates of decay and particle emission are the same. There are instances, however, in which at least two particles are emitted. In such instances, the total rate of particle emission is not a measure of activities in Curies. The Curie is defined in terms of the "actual rate of disintegration" and "data based on particle emission" and may require correction for various reasons; therefore, if the activity of a sample is to be accurately calculated from experimental data, the decay scheme of the radionuclide must be taken into account. (Decay schemes and types of emissions are discussed in Module 1-5.)

SPECIFIC ACTIVITY

In work with radioactive nuclides, one important concept often encountered is specific activity. This concept is defined as the activity in Curies per unit mass of the substance. Specific activity of a radioactive nuclide is higher if more nuclei decay in a unit time if it has a shorter half-life. Usually, specific activity is expressed in Curies/gram (or Ci/gram) of the radionuclide.

EXERCISES

1. Given: A radioactive source has a decay constant of $0.3\ \text{day}^{-1}$ and the decay rate is presently 100 Curies. How long will it be until the source strength is reduced to 10 Curies?

$$A = A_o e^{-\lambda t}.$$

2. What is the activity of a sample if it contains 100 grams of radium-226?

$$A = \lambda N.$$

$$\lambda = \frac{0.693}{T_{1/2}}.$$

$$N = \frac{N_a M}{\text{g-at.wt}}$$

MATERIALS

1 Scaler-ratemeter with Geiger-Mueller probe.
1 Short-lived radionuclide with stable daughter.
1 Sample-pan holder.
1 Semilog graph paper, two- or three-cycle.
1 Table of natural logarithms or calculator with natural log function.

PROCEDURES

PLOTTING OF A SIMPLE RADIOACTIVE DECAY CURVE

1. Turn the scaler-ratemeter on; let it warm up.
2. Connect an end-window Geiger-Mueller probe to the scaler-ratemeter. Record the identification number of the scaler-ratemeter and probe on Data Table 1-4-1.
3. Set the high voltage to an operating value determined from previous experiment (or specified by instructor).
4. Place Geiger-Mueller probe in the sample-pan holder.
5. Record operating voltage, date and time on Data Table.
6. Take a 5-minute initial background count; record number of counts and count rate on Data Table.
7. Obtain a short-lived radionuclide from instructor. Record radionuclide type, activity measured and date of purchase on Data Table.
8. Place radionuclide on shelf in sample-pan holder so that the count rate is between 1000 - 10,000 cpm.
9. Record shelf position on Data Table.
10. Take one-minute duration counts at intervals specified

by instructor. Record count rate (gross), clock time, and elapsed time since initial count on Data Table.

11. Repeat one-minute duration counts until count rate is less than 50% of initial count rate. Record results on Data Table.
12. Take a final five-minute background count; record count on Data Table.
13. Find average of initial and final background count rates; record result on Data Table.
14. Subtract average background count rate from total (gross) count rate to obtain net count rate; make calculations for all data collected in item 10 (above). Record net count rates on Data Table.
15. Plot net count rate versus time on semilog graph paper (net count rate plots as ordinate - vertical axis - and time as the abscissa - horizontal axis). Be sure to properly label graph, including title and axes.
16. Draw straight line through points (there should be approximately the same number of points on either side of line) with greater weight given to those points representing the higher counting rates.

DETERMINATION OF HALF-LIFE DIRECTLY FROM STRAIGHT LINE ON GRAPH

1. Read value at "zero time" on straight line; record this value as the initial count rate on Data Table 1-4-2.
2. Take one-half of initial count rate; record this value on Data Table.

3. From straight line, read time corresponding to one-half count rate; record this time as "half-life" on Data Table.
4. Obtain from instructor the accepted value of half-life for the radionuclide used; record on Data Table.
5. Calculate percent error from equation on Data Table; use accepted half-life obtained from instructor.

DETERMINATION OF HALF-LIFE FROM STRAIGHT LINE ON GRAPH; USE GIVEN EQUATIONS

$$\lambda = \frac{\ell n\ (A_0/A)}{\text{time}} \,. \qquad \text{Eq. 1-4-5}$$

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda} \,. \qquad \text{Eq. 1-4-6}$$

1. Read value at "zero time" on straight line; record this value as A_0 on Data Table 1-4-3.
2. Take natural log of A_0; record on Data Table.
3. Choose any arbitrary time on graph (except time determined in second procedure); record on Data Table.
4. From straight line, read count rate corresponding to time chosen in item 3; record this count rate as A on Data Table.
5. Take natural log of A; record on Data Table.
6. Calculate decay constant on Data Table (after substituting the appropriate values).
7. Calculate half-life on Data Table (after substituting in the appropriate value for decay constant).

8. Calculate percent error (from equation) on Data Table; use accepted half-life obtained from instructor.

DATA TABLE

DATA TABLE 1-4-1

Equipment identification
(counter and probe): ______________________________
Operating voltage: __________________
Date: __________________
Time: __________________
Background -
Initial background count: __________________
Initial background count rate: __________________
Final background count: __________________
Final background count rate: __________________
Average background count rate: __________________
Radionuclide identification -
Radionuclide type: __________________
Activity (microcuries) __________________
Date of purchase: __________________
Shelf position (number from top): __________________

DECAY DATA TABLE

Clock Time	Elapsed Time	Gross Count Rate	Net Count Rate

DATA TABLE 1-4-2

Initial count rate: ____________

One-half of initial count rate: ____________

Time corresponding to above count rate: ____________

Experimental half-life: ____________

Accepted half-life of radionuclide used: ____________

Percent error

$$= \frac{(\text{Experimental half-life}) - (\text{accepted half-life}) \times 100}{(\text{Accepted half-life})}$$

$$= \frac{(\quad) - (\quad)}{(\quad)} \times 100\%$$

$= \underline{\hspace{6cm}}\%.$

DATA TABLE 1-4-3

Initial count rate, A_0: ____________________

$\ell n\ (A_0)$: ____________________

Arbitrary time: ____________________

Count rate, A: ____________________

$\ell n\ (A)$: ____________________

$$\text{Decay constant, } \lambda = \frac{\ell n\ (A_0) - \ell n\ (A)}{\text{time}}$$

$$\lambda = \frac{(\qquad) - (\qquad)}{(\qquad)}$$

$$= \underline{\qquad\qquad\qquad}$$

Experimental half-life:

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda} = \frac{0.693}{(\qquad)} = \underline{\qquad\qquad\qquad\qquad}.$$

Percent error =

$$\frac{(\text{Experimental half-life}) - (\text{Accepted half-life})}{(\text{Accepted half-life})} \times 100\%$$

$$= \frac{(\qquad) - (\qquad)}{(\qquad)} \times 100\% = \underline{\qquad\qquad\qquad\qquad}\%.$$

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Oman, Robert M. *An Introduction to Radiologic Science*. New York: McGraw-Hill, 1975.

TEST

To do problems in this test, students (trainees) need one of the following: slide rule, logarithm table, or calculator with natural logs.

Select and circle the letter of the best response to each of the following definitions or statements.

1. A measure of the number of atomic nuclei decaying during any time period:
   a. Curie
   b. Activity
   c. Avogadro's number
   d. Nucleon

2. The probability of disintegration or transformation per nucleus in unit time:
   a. decay constant
   b. half-life
   c. mass absorption coefficient
   d. nuclear force

3. The time in which fifty percent of the atoms of a particular radioactive nuclide decay:
   a. positron decay
   b. stability
   c. radioactive decay
   d. half-life

4. The spontaneous disintegration or transformation of one nuclide into another:
   a. radioactive decay
   b. fusion
   c. half-value layer
   d. specific activity

5. The energy that pulls both protons and neutrons toward each other:
   a. resolving time
   b. spontaneous disintegration
   c. nuclear force
   d. intensity

6. The state of nonradioactivity:

   a. gross count rate
   b. inverse square law
   c. dose rate
   d. stability

7. A particle coming from the nucleus of an atom:

   a. electron
   b. nucleon
   c. radioactive waste
   d. nucleus

8. Mass in grams given in multiples of the atomic weight:

   a. Curie
   b. atomic number
   c. Avogadro's Number
   d. gram-atomic weight

9. A measure of disintegrations per second per unit mass:

   a. atomic mass
   b. specific activity
   c. alpha emission
   d. decay constant

10. A measure of a unit of radioactivity:

   a. Farad
   b. Coulomb
   c. Hertz
   d. Curie

11. The mass of any given nuclide:

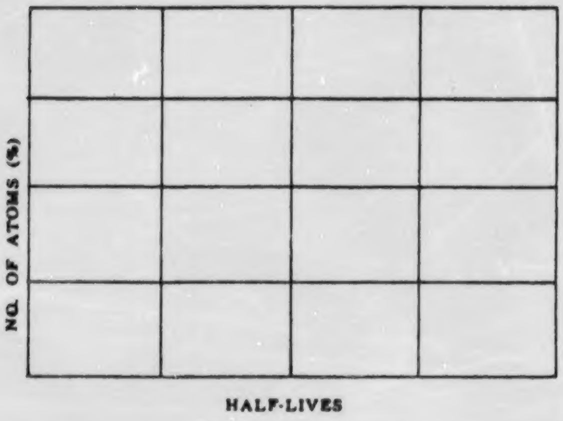
   a. neutron
   b. alpha radiation
   c. atomic weight
   d. atmoic number

12. The amount of atoms present in one gram-atom or in the gram-atomic weight of a nuclide?

- a. Avogadro's Number
- b. isometric transition
- c. decay scheme
- d. gamma photon

13. Give the general exponential relationship for radioactive decay, $N = N_0 e^{-\lambda t}$, write the equation that shows the relationship between decay constant and half-life.

14. Draw a typical graph of activity vs. time for a period of four half-lives. Use the grid below for your graph.



15. Assume that at time A the activity of a sample is 3600 gpm, at time B, twenty-four hours later, the activity is 2800 cpm. Calculate the decay constant and half-life.

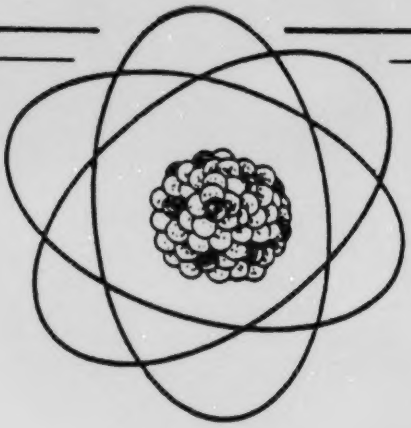
Calculate the following.

16. Assuming a half-life of 2 hours, what fraction of the radioactive material will decay in 15 minutes?

17. What is the number of atoms present in a 10 gram sample of Boron-10?

18. How many disintegrations per second (and Curies) occur in a 10-gram sample of Cobalt-60? (Cobalt-60 Half-Life = 5.3 yrs.)

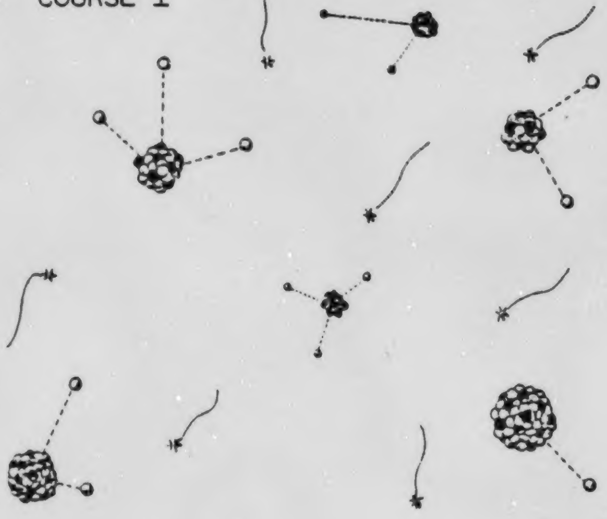
19. What is the specific activity of a 10-gram sample that has an activity of 3 Curies?



NUCLEAR TECHNOLOGY

MODULE 1-5 DECAY PROCESSES AND SCHEMES

RADIATION PHYSICS
COURSE I



COURSE MODULES

COURSE 1 RADIATION PHYSICS

	MODULE 1-1	Introduction to Radiation Laboratory Safety
	MODULE 1-2	Basic Radiation Detection and Measuring Equipment
	MODULE 1-3	Atomic Structure and Radioactivity
	MODULE 1-4	Radioactive Decay and Half-life
⇨	MODULE 1-5	Decay Processes and Schemes
	MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Each radionuclide has its own unique pattern of decay. Three aspects that characterize the radioactive decay of a given radionuclide are decay rate (half-life), type of emission and energy of emission.

Identification of a particular radionuclide may depend upon how well these three factors can be determined. Many radionuclides have similar decay-rates, but the type and energy of their emissions may differ greatly. Other radionuclides may have similar types and energies of emission, but their decay-rates may differ greatly.

Decay rates and half-lives were discussed in a preceding module. The different types and energies of emissions resulting from radioactive decay are discussed in this module. The student learns how to determine, identify and measure emissions.

MODULE PREREQUISITES

The student should have a general introduction to radioactive decay and half-live, as presented in Module 1-4 of this course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Perform the following tasks related to radioactive decay processes:
    - Identify two main types of particulate radiation; give their approximate speed, mass in AMU, electrical charge and penetrating ability.
    - Briefly define electromagnetic radiation, gamma radiation and photons.
    - For each of the decay processes listed below, write a sample decay equation and draw a sample decay scheme:
        - Alpha emission.
        - Beta emission.
        - Positron emission.
        - K-capture.
        - Isomeric transition.
2. Read and interpret complex radioactive decay schemes (such as those published in the Radiological Health Handbook, including:
    - Type and energy levels.
    - Branching percentages. Write the decay equations from the decay schemes.
3. Read and interpret the Chart of the Nuclides and perform the following tasks:
    - Describe layout by identifying horizontal axis, vertical axis and diagonals.
    - Indicate the position of any particular nuclide, given labeled axes but not identifications in individual squares.

Indicate on Chart of the Nuclides the position of a daughter nucleus relative to its parent nucleus for each decay process given in objectives.

Trace each of four natural decay series down to a stable nuclide; use Chart of the Nuclides.

TYPES OF RADIATION

There are two main types of radiation. One type is composed of tiny, energetic particles called "particulate" radiation. The other type consists of very short waves called "electromagnetic" radiation, such as x-rays and gamma rays. Both kinds of radiation may be given off by radioactive atoms. Both kinds of radiation propagate energy through space.

PARTICULATE RADIATION

For the purpose of this module radiation represents the movement of tiny subatomic particles through space. The particles have mass (or weight) and, in most cases, an electrical charge - they transfer energy from one point to another. While traveling at high speeds, they strike (or are deflected by) other particles, such as orbital electrons or nuclei of atoms, or they may be stopped and captured by atoms or their nuclei.

As these particles undergo velocity changes, their kinetic energies change (that is, when they are slowed down or stopped, they release energy).

When particles carry an electrical charge, electrical or magnetic forces affect their motion as well. When a fast-moving particle transfers energy to an atom, it may cause the atom to lose energy in the form of heat and light, or it may cause ionization to take place.

The particulate radiations of primary concern in this module are alpha and beta particles. Other particulate radiation, such as neutrons and protons, is discussed in later modules.

Alpha Particles

Alpha particles are relatively heavy, each containing two protons and two neutrons. Usually they are ejected as a result of disintegrations of radioactive nuclei of various heavy elements. The particles themselves are ionized helium nuclei.

When an alpha particle slows down in its passage through matter, it generally picks up two free electrons and becomes a neutral atom of helium. An alpha particle has an atomic weight of 4.00277 AMU and carries two units of positive electrical charge.

Alpha particles are emitted from radioactive materials at speeds in a range (generally) from 1.6×10^5 to 1.6×10^6 cm/sec (2,000 to 20,000 miles per second). Because of their size and relatively slow speeds, they travel only a few centimeters in air before being stopped and they may be stopped by a sheet of paper.

Alpha particles are emitted with an energy ranging from 4 to 10 million electron volts (MeV) usually. Radium-226 is a commonly used alpha-emitter.

Beta Particles

Beta particles originate in the nucleus of an atom. Once outside the nucleus, they become high-speed electrons, with one unit of negative charge and an at-rest mass of about 1/1837 that of a proton.

In some nuclear transformations, the nucleus may emit a positively-charged electron; these are called positrons.

Beta particles, emitted at very high velocities approaching the speed of light, have a range of several feet in air and can be stopped by a thin sheet of aluminum or several sheets of paper. The energy of beta particles typically ranges up to 3.15 MeV, with most having an energy about 1 MeV.

Commonly used beta-emitters include carbon-14 and strontium-90; sodium-22 and zinc-65 are among the more common positron-emitters.

ELECTROMAGNETIC RADIATION

Electromagnetic radiation can be considered to consist of discrete units (photons) of energy that move through space with the speed of light (186,000 miles per second). Unlike alpha and beta particles, photons have no at-rest mass. Visible light, radar, radio waves, infrared radiation, x-rays and gamma radiation are types of electromagnetic radiation. (A detailed discussion of electromagnetic radiation is given in Module 1-6, "Basic Properties of Gamma Radiation.") The kinds of electromagnetic radiation of concern in this study include x-ray and gamma radiation.

Gamma radiation, in reality, consists of high-energy electromagnetic waves, and is often referred to as γ-rays. These rays are highly penetrating and may still be detected after passing through several inches of steel. The rays of interest to this study - those emitted by natural radioactive elements - have energies from about 0.04 to 3.2 MeV.

X-rays and gamma rays are similar in that both are electromagnetic radiation. They differ, however, in their origin. When the nucleus of a radioactive atom emits an alpha or beta particle, the daughter nucleus frequently is left in a high-energy or excited state. The excess energy is usually emitted as gamma radiation, which brings the nucleus to a more stable energy condition. Thus, gamma rays originate in the nuclei of atoms.

X-rays, on the other hand, are produced when a stream of fast-moving (high-energy) electrons is slowed down upon striking a suitable target. Collisions between the fast-moving electrons and the target atoms cause electron transitions within the atomic orbital shells, giving rise to the photons of energy called characteristic x-rays.

DECAY SCHEMES

As radioactive materials disintegrate, they follow rather well defined decay schemes (Figure 1-5-1). Decay schemes show the type of radiation particles and photons emitted as an unstable atom (parent) decays to another type of atom (daughter). The daughter atom can also be a radioactive atom and undergo further decay. In such schemes, a horizontal line is drawn to indicate the energy level of a radioactive atom (parent). Below this line, another horizontal line indicates ground level energy for the daughter atom. An arrow

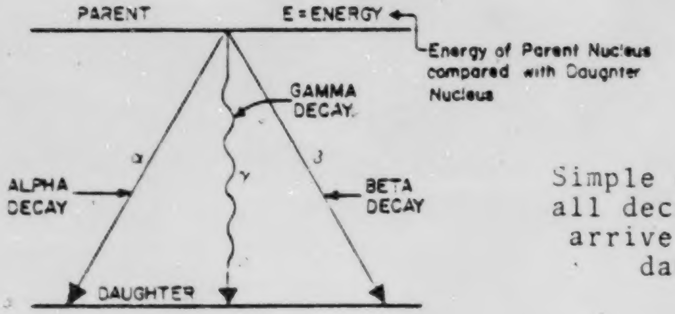

PARENT
E = ENERGY
Energy of Parent Nucleus compared with Daughter Nucleus
GAMMA DECAY
α
γ
β
ALPHA DECAY
BETA DECAY
DAUGHTER

Figure 1-5-1.
Simple decay process. (Note: all decays do not necessarily arrive at a common energy daughter product.)

sloping down and to the right indicates emission of a negative beta particle; a wavy line drawn straight down indicates emission of a gamma photon; a straight line drawn down to the left indicates alpha emission. Also, in these three occurrences, loss of negative charge, no change in charge state and loss of positive charge take place. Furthermore, diagonal displacement directions indicate a change to new elements.

Several modes of decay may be possible for a radioactive nuclide, so that several particles and gamma rays of discrete energies may be emitted. For a particular nucleus, each mode of decay has a definite probability - energy distributed between emitted particles becomes a characteristic of the nuclide.

SPECIFIC DECAY TYPES

Several decay types should be considered in this discussion.

ALPHA (α) EMISSION

In alpha decay, the initial nuclide loses two positive charge units and four nuclear mass units. The decay scheme or process can be represented as follows:

$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}X + \, ^{4}_{2}\alpha$$

where X is the chemical symbol and $^{4}_{2}\alpha$ (also written as α and $^{4}_{2}$He) is the alpha particle. (Note: The sum of the mass numbers (superscripts) on the left side of the arrow equals those on the right side. The same is true for the subscripted atomic numbers.)

Alpha emission occurs, as a rule, in the heaviest natural elements and the transuranic elements (those with atomic numbers above uranium 92), particularly those that are part of the disintegration series of natural radioactive elements (see section on Natural Radioactive Decay Chains). The decay process is accompanied, in most instances, by emission of gamma rays:

$$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn} + {}^{0}_{0}\gamma$$

where the emission of gamma rays is indicated formally, although it is sometimes "understood" and left out of the decay equation. It is best to include it for completeness.

In the decay scheme of ^{226}Ra (Figure 1-5-2), 100 de-

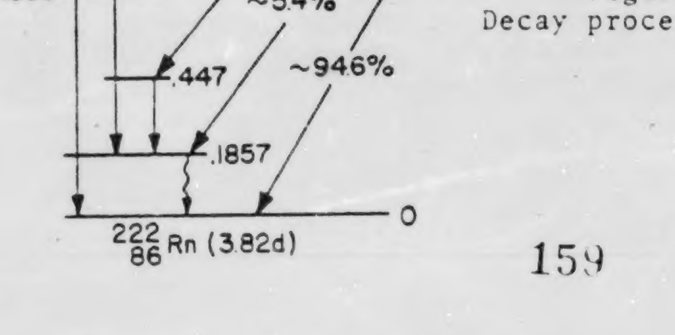


Figure 1-5-2.
Decay process for $^{226}_{88}$Ra.

cay processes are indicated; 94 alphas are emitted, with 4.78 MeV energy; 6 alphas are emitted, with 4.59 MeV energy; 6 gamma rays are emitted, with 0.19 MeV. Also shown are the half-lives (1602 years for ^{226}Ra and 3.82 days for ^{222}Rn), and the energy (4.782 MeV) of the ^{226}Ra nucleus relative to the ^{222}Rn nucleus.

Other examples of alpha emission include:

$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{4}_{2}\alpha + {}^{206}_{81}\mathrm{T\ell}$$

and

$$^{239}_{94}\mathrm{Pu} \rightarrow {}^{4}_{2}\alpha + {}^{235}_{92}\mathrm{U}.$$

BETA (β^-) EMISSION

In beta emission, the residual nucleus becomes the next higher element (the atomic number is increased by one); the atomic mass is essentially unchanged:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e$$

where the beta particle is represented either by $^{0}_{-1}e$ or β^- or $^{0}_{-1}\beta$.

This type of decay, which most usually is accompanied by gamma rays, is typical for nuclei possessing a neutron excess (in comparison with a stable composition). The electron is ejected from the nucleus, and the proton remains, raising the atomic number by one and leaving the mass number the same.

Recall that a neutron can be considered as a p^+ and a β^-.

An example of pure beta decay (Figure 1-5-3) may be stated as follows:

$$^{32}_{15}p \rightarrow {}^{0}_{-1}e + {}^{32}_{16}S.$$

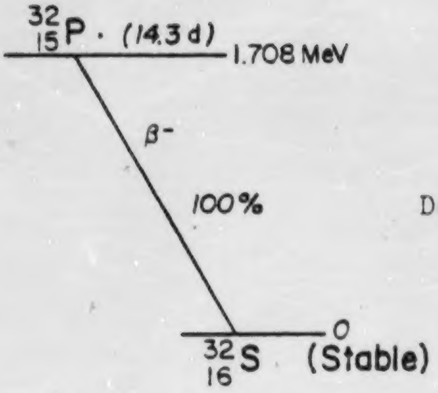


Figure 1-5-3.
Decay scheme for $^{32}_{15}P$.

The β^- decay for ^{60}Co may be given as follows:

$$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + \gamma_1 + \gamma_2.$$

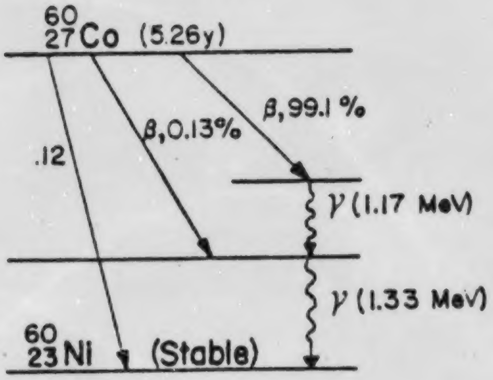

$^{60}_{27}$Co (5.26y)
β,99.1 %
β,0.13%
.12
γ (1.17 MeV)
γ (1.33 MeV)
$^{60}_{23}$Ni
(Stable)

Figure 1-5-4.
Decay scheme for $^{60}_{27}$Co.

Notice that about one in every eight Co-60 atoms emits a beta particle and then emits a gamma photon of 1.33 MeV energy in decaying to ^{60}Ni. About 99+ percent of the Co-60 atoms emit a beta particle and then emit a gamma photon of 1.17 MeV and subsequently another of 1.33 MeV.

The final product for each decay branch is stable Ni-60.

Another example of the decay, for ^{137}Cs (Figure 1-5-5), may be stated as follows:

$$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\mathrm{e} + \gamma_1$$

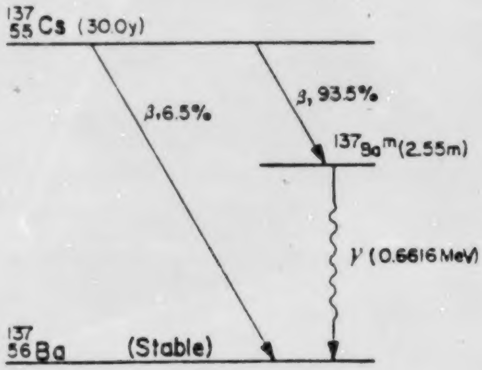

$^{137}_{55}$Cs (30.0y)
β,6.5%
β, 93.5%
^{137}Ba^{m}(2.55m)
γ (0.6616 MeV)
$^{137}_{56}$Ba
(Stable)

Figure 1-5-5.
Decay scheme for $^{137}_{55}$Cs.

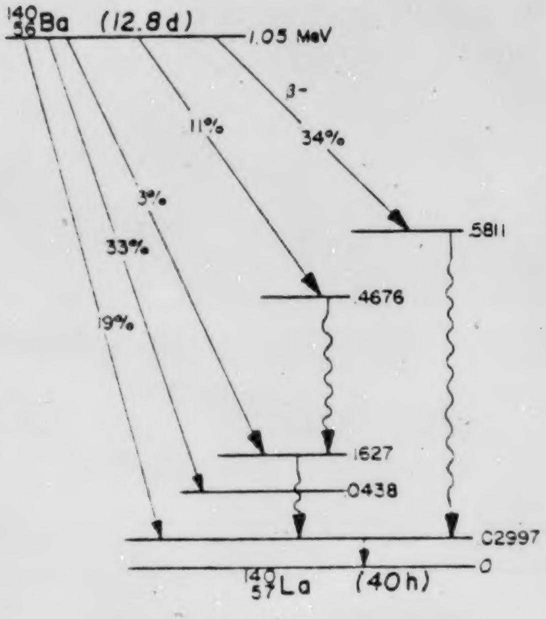
$$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba + {}^{0}_{-1}e + \gamma_1 .$$

About 6.5 percent of all Cs-137 atoms emit beta particles without emitting gamma photons. The other 93.5 percent emit beta particles before emitting gamma photons of 0.666 MeV. Stable Ba-137 is the final product of either decay branch.

An example of complex beta decay with numerous gamma emissions is found in the decay of barium-140 to lanthanum-140:

$$^{140}_{56}Ba \rightarrow {}^{140}_{57}La + {}^{0}_{-1}e.$$

This decay scheme, with all the gammas given off, is shown in Figure 1-5-6.



$^{140}_{56}$Ba (12.8d)
1.05 MeV
β-
11%
34%
3%
33%
19%
.5811
.4676
.1627
.0438
C2997
0
$^{140}_{57}$La (40h)

Figure 1-5-6.
Decay scheme for $^{140}_{56}$Ba.

Another example of complex beta decay (Figure 1-5-7) may be written as follows:

$$^{140}_{57}La \rightarrow {}^{140}_{58}Ce + {}^{0}_{-1}e.$$

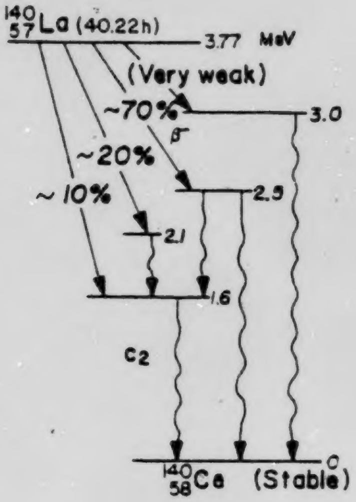

$^{140}_{57}$La (40.22h)
3.77 MeV
(Very weak)
~70%
β^-
~20%
~10%
3.0
2.5
2.1
1.6
c2
0
$^{140}_{58}$Ce (Stable)

Figure 1-5-7.
Decay scheme for $^{140}_{57}$La.

POSITRON (β+) EMISSION

In positron (β+) emission, the residual nucleus moves to a lower atomic number element (the atomic number is reduced by one); the atomic mass remains essentially unchanged:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + {}^{0}_{+1}e$$

where the positron is represented either by $^{0}_{+1}e$ or β^+.

This type decay, usually accompanied by gamma rays, is typical for nuclei possessing a proton excess. Positron emission actually occurs by the conversion of one of the excess protons into a positron and a neutron:

$$^{1}_{1}p \rightarrow {}^{0}_{+1}e + {}^{1}_{0}n.$$

The preceding reaction for ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X$ requires an excess energy of 1.02 MeV for completion; that is, the radioactive nucleus must have an energy at least 1.02 MeV greater than the daughter nucleus, otherwise the reaction cannot take place.

Positron decay occurs for artificial radioactive nuclei of low mass number, if the nuclei contain too many protons (compared with a stable composition). Also, the radioactive nuclei must have at their disposal an energy excess of 1.02 MeV (over that of the daughter nucleus).

Note: K-capture, explained later, can also occur under these circumstances.

The emitted positrons unite with electrons within a very short time, and the at-rest mass of both particles changes into two 0.51 MeV γ-rays called "annihilation radiation."

An example of $\beta+$ (${}^{14}_{8}O$ positron) decay (Figure 1-5-8) may be written as follows:

$${}^{14}_{8}O \rightarrow {}^{0}_{+1}e + {}^{14}_{7}N.$$

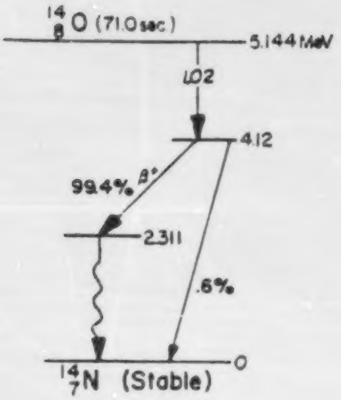

${}^{14}_{8}O$ (71.0sec)
5.144 MeV
1.02
4.12
99.4% β^+
2.311
.6%
0
${}^{14}_{7}N$ (Stable)

Figure 1-5-8.
Decay scheme for ${}^{14}_{8}O$.

Note that in the decay scheme, 1.02 MeV is absorbed in creating the positron. A positron of energy, 1.8 MeV (4.1 MeV - 2.3 MeV) and a gamma ray of 2.3 MeV are emitted.

An example of a complex positron decay (Figure 1-5-9) may be written as follows:

$${}^{35}_{18}Ar \rightarrow {}^{0}_{-1}e + {}^{35}_{17}Cl.$$

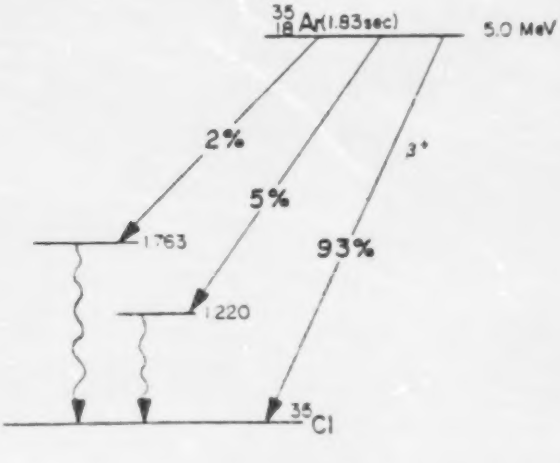

${}^{35}_{18}Ar$(1.83sec)
5.0 MeV
2%
5%
β^+
93%
1.763
1.220
${}^{35}Cl$

Figure 1-5-9.
Decay scheme for ${}^{35}_{18}Ar$.

K-CAPTURE

The capture of an electron by the nucleus from the innermost electron shell or orbit (called the K-shell) can occur in a nucleus with a proton excess. The end effect for the nucleus is the same as in β+ decay. The void created in the K-shell is filled by the capture of an outer orbital electron; this electron transition causes the emission of characteristic x-rays. In the example (Figure 1-5-10), all decays are to various excitation levels of $^{51}_{28}$V.

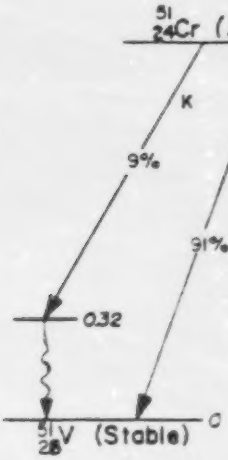
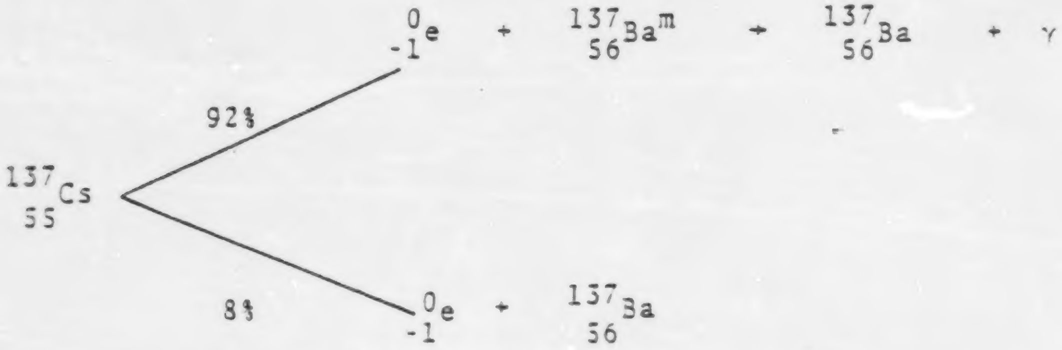


Figure 1-5-10.
Typical K-capture process.

ISOMERIC TRANSITION

The residual nucleus resulting from particle emission or K-capture may be left in an excited state. The energy difference between the excited nucleus and the residual nucleus (ground state) is, in most cases, immediately radiated (within about 10^{-18} sec) in the form of one or more γ-rays. For some nuclides, however, the excited intermediate nucleus lasts considerably longer in a metastable state, decaying radioactively with a well-determined half-life.

Nuclides with the same atomic numbers and mass numbers, but with different energies, are called isomers; that is, a nuclide in an excited state and a similar nuclide in the ground state are called isomers. As an example, ^{137}Cs may be indicated as follows:


$^{137}_{55}\mathrm{Cs}$
92%
$^{0}_{-1}e + {}^{137}_{56}\mathrm{Ba}^{m} \rightarrow {}^{137}_{56}\mathrm{Ba} + \gamma$
8%
$^{0}_{-1}e + {}^{137}_{56}\mathrm{Ba}$

In this example of isomeric transaction, the superscript, m, denotes a metastable state; i.e., an excited nucleus not in the ground state.

The excited isomer, in a metastable state, denoted by $^{137}_{56}\mathrm{Ba}^{m}$ (Figure 1-5-11), decays to the ground state $^{137}_{56}\mathrm{Ba}$ by gamma emission with a 2.6 minute half-life.

Other types of nuclear emissions, including neutron emission and spontaneous fission, which occur with low probabilities, are discussed in later courses.

Figure 1-5-11.
Decay scheme for $^{137}_{55}Cs$.

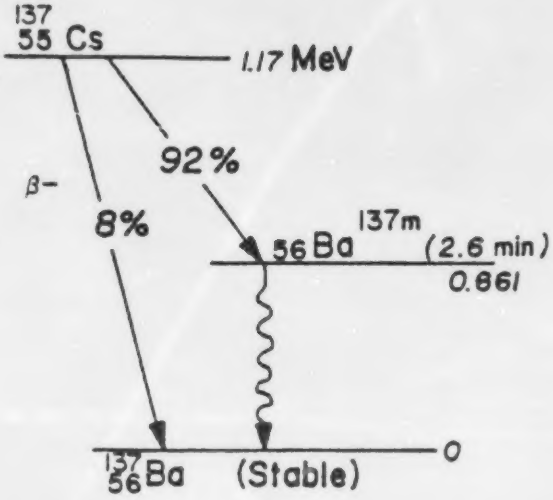


CHART OF THE NUCLIDES

A vast amount of information has been collected regarding the behavior of stable and unstable nuclei. This information, published in a form that enables the characteristics of any nuclide to be determined immediately, appears in the partial Chart of the Nuclides (Figure 1-5-12).

NOTE: The complete chart is reproduced in many textbooks and handbooks (including the Radiological Health Handbook) and is also available as a wall chart. Each student should obtain a copy.

In this chart, atomic number Z is plotted against the number of neutrons A-Z (where A is the mass number). Each nuclide occupies a square, and relevant information regarding a nuclide is printed inside its square. All nuclides on the same horizontal line have the same atomic number (hence are isotopes); all nuclides with the same mass number lie on a 45° diagonal line (running from upper left to lower right).

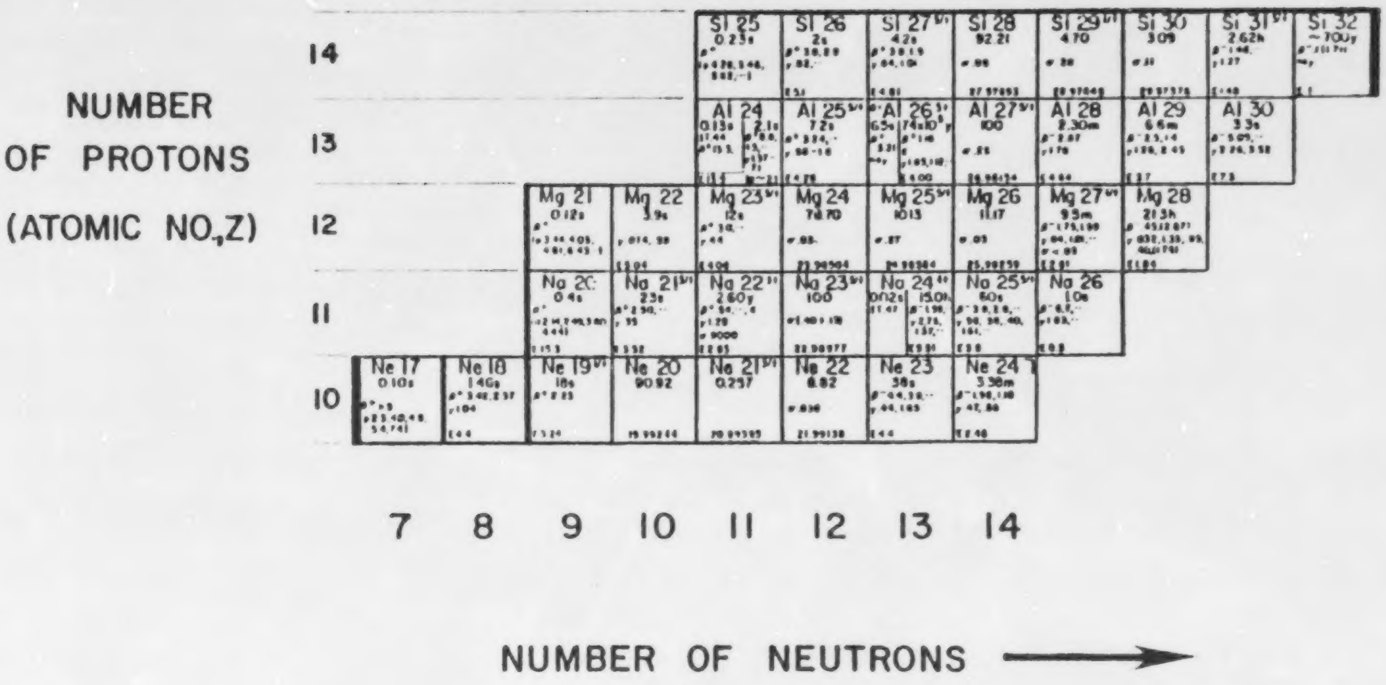

NUMBER OF PROTONS (ATOMIC NO.,Z)
14
13
12
11
10
Si 25
Si 26
Si 27
Si 28
Si 29
Si 30
Si 31
Si 32
Al 24
Al 25
Al 26
Al 27
Al 28
Al 29
Al 30
Mg 21
Mg 22
Mg 23
Mg 24
Mg 25
Mg 26
Mg 27
Mg 28
Na 20
Na 21
Na 22
Na 23
Na 24
Na 25
Na 26
Ne 17
Ne 18
Ne 19
Ne 20
Ne 21
Ne 22
Ne 23
Ne 24
7
8
9
10
11
12
13
14
NUMBER OF NEUTRONS

Figure 1-5-12. A portion of the chart of the nuclides.

Many nuclide charts contain additional information, which has been omitted from the sample chart (Figure 1-5-12) for clarity.

Stable, naturally radioactive and artificial nuclides are differentiated by different colors or shadings of squares. In each instance, however, both the symbol and the mass number are shown. For stable nuclides, the natural abundance is given (Figure 1-5-13).

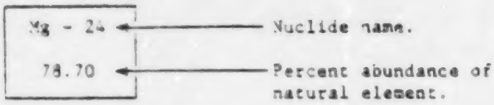

Mg - 24
78.70
Nuclide name.
Percent abundance of natural element.

Figure 1-5-13.
Typical stable nuclide square.

For radioactive isotopes, the half-life, the mode or modes of decay, and the energies of the emitted particles or gamma rays are given (Figure 1-5-14).

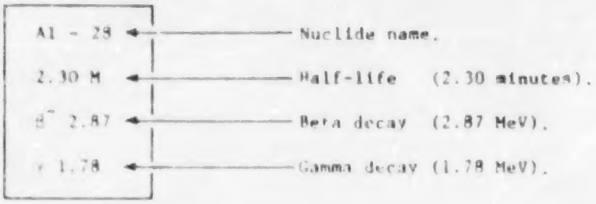

Al - 28
2.30 M
β^- 2.87
γ 1.78
Nuclide name.
Half-life (2.30 minutes).
Beta decay (2.87 MeV).
Gamma decay (1.78 MeV).

Figure 1-5-14.
Typical radioactive nuclide square.

Examples of information that can be obtained from the chart (Figure 1-5-12) are included in Table 1-5-1.

TABLE 1-5-1

Nuclide	Stable or Radioactive	Half-Life if Radioactive	Abundance if Stable	Decay Mode
Si-28	Stable	-	92.21	-
Mg-27	Radioactive	9.5 minute	-	β^-, γ
Na-22	Radioactive	2.6 year	-	β^-, γ

Not enough information is given in the chart to describe complete decay schemes, including the percent branching; even so, the nuclide chart provides an extremely valuable source of information on properties of stable and unstable nuclides.

Also, the chart provides information on the daughter products of radioactive nuclides (Figure 1-5-15), such as

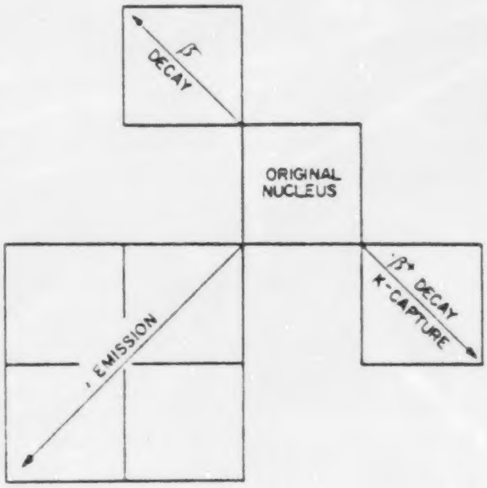


Figure 1-5-15.
Parent-daughter relationship from Chart of the Nuclides.

location of the daughter relative to the parent nucleus. Consider beta decay: the daughter nucleus is displaced one square up and to the left of the original nucleus.

EXAMPLE

Given: Diagrams (Figures 1-5-12 and 1-5-14).

Find: Daughter of Mg-23. Verify results by writing decay equation.

Solution: The Mg-23 radioisotope decays by a positron (β^+) and gamma emission (Figure 1-5-12). Gamma emission is neglected when determining daughter because gamma emission does not change nuclide position in chart. The daughter is found to be located one square down and to the right of the parent (Figure 1-5-15); therefore (Figure 1-5-12), the daughter of Mg-23 is Na-23, which is stable and accounts for 100% of all natural Na (sodium).

Identity of the daughter is also shown by the decay equation:

$$^{23}_{12}\mathrm{Mg} \rightarrow {}^{0}_{+1}e + {}^{23}_{11}\mathrm{Na}.$$

NATURAL RADIOACTIVE DECAY CHAINS

In much of the preceding discussion, it has been assumed that, when an excited atom loses energy, it reaches a stable configuration. This assumption is not necessarily a rule of thumb. In fact, it rarely occurs in practice. Even though an excited atom in an unstable state loses energy in going to another configuration, the second configuration may also be unstable and decay with its own half-life to a third configuration, and so on. Such a series of radioactive transformations is called a radioactive chain of parents and daughters.

Four of these radioactive decay chains exist in nature. The name of each chain, or series, the long-lived parent, its half-life, and the end product are given in Table 1-5-2.

TABLE 1-5-2
RADIOACTIVE CHAINS OF PARENTS AND DAUGHTERS

Series Name	Long-Lived Parent	Half-Life of Parent	Stable End-Product
Thorium	$^{232}_{90}\text{Th}$	1.39×10^{10} years	$^{208}_{82}\text{Pb}$
Neptunium	$^{237}_{93}\text{Np}$	2.20×10^{6} years	$^{209}_{83}\text{Bi}$
Uranium	$^{238}_{93}\text{U}$	4.51×10^{9} years	$^{206}_{82}\text{Pb}$
Actinium	$^{235}_{92}\text{U}$	7.1×10^{8} years	$^{207}_{82}\text{Pb}$

Each long-lived parent can be traced to a stable end product on the Chart of the Nuclides.

EXERCISES

None.

MATERIALS

1 Chart of the Nuclides.
1 Set, radioactive decay schemes (such as in Radiological Health Handbook).

CHART OF THE NUCLIDES

The following procedures are designed to teach the student to use the Chart of the Nuclides.

1. On Data Table 1-5-1, indicate for each listed nuclide the following:
    - Stable or radioactive.
    - Half-life (if radioactive).
    - Percentage abundance (if stable).
    - Type and energy of emissions (if radioactive).
    - Part of a natural radioactive decay chain (yes or no).
2. On Data Table 1-5-2, indicate (for the listed radionuclides) the following:
    - Type of emission.
    - Daughter product.
    - Daughter condition (stable or radioactive).
    - Half-life.
3. On Data Table 1-5-3, write decay equations for indicated radionuclides.
4. On lined white paper, trace each of the four naturally occurring radioactive decay chains to its stable element; write radioactive equations used.
5. Use decay schemes, such as those given in the Radiological Health Handbook: draw decay schemes for radionuclides listed in Data Table 1-5-4; identify the following:
    - Energy of radioactive parent, compared with daughter.
    - Percent contribution of all branching components.

Types and energies of all emissions for all branching components. (Be sure to give decay energies, not energy above ground state.)

INCLUDE NO EXTRANEOUS INFORMATION.

DATA TABLE 1-5-1
CHART OF THE NUCLIDES

Nuclide	Name of Element	Stable or Radioactive	Percentage Abundance	Type and Energy of Emissions	Part of Radioactive Decay Chain
1. ^{10}B					
2. ^{1}H					
3. ^{14}C					
4. ^{16}O					
5. ^{22}Na					
6. ^{28}Al					
7. ^{40}K					
8. ^{59}Co					
9. ^{137}Cs					
10. ^{112}Ag					
11. ^{122}In					
12. ^{131}I					
13. ^{197}Au					
14. ^{209}Bi					
15. ^{226}Ra					
16. ^{239}Pu					
17. ^{235}U					
18. ^{238}U					
19. ^{252}Cf					
20. ^{210}Po					

DATA TABLE 1-5-2
CHART OF THE NUCLIDES

Nuclide	Type of Emission	Daughter Product	Daughter Stable or Radioactive	Daughter Half-Life
1. ^{227}Ra				
2. ^{209}Pb				
3. ^{199}Hg				
4. ^{137}Cs				
5. ^{90}Sr				
6. ^{99}Tc				
7. ^{16}N				
8. ^{10}Be				
9. ^{27}Si				
10. ^{48}V				
11. ^{62}Cu				
12. ^{51}Cr				
13. ^{59}Ni				
14. ^{69}Zn				
15. ^{40}K				
16. ^{3}H				
17. ^{11}C				
18. ^{18}F				
19. ^{110}Ag				
20. ^{110}Ag				

DATA TABLE 1-5-3
RADIOACTIVE DECAY EQUATIONS

Indicate whether or not gamma rays are emitted.

1. $^{227}\mathrm{Ra} \rightarrow$ ____________ + ____________
2. $^{209}\mathrm{Pb} \rightarrow$ ____________ + ____________
3. $^{199}\mathrm{Hg} \rightarrow$ ____________ + ____________
4. $^{137}\mathrm{Cs} \rightarrow$ ____________ + ____________
5. $^{90}\mathrm{Sr} \rightarrow$ ____________ + ____________
6. $^{99}\mathrm{Tc} \rightarrow$ ____________ + ____________
7. $^{16}\mathrm{N} \rightarrow$ ____________ + ____________
8. $^{10}\mathrm{Be} \rightarrow$ ____________ + ____________
9. $^{27}\mathrm{Si} \rightarrow$ ____________ + ____________
10. $^{48}\mathrm{V} \rightarrow$ ____________ + ____________
11. $^{62}\mathrm{Cu} \rightarrow$ ____________ + ____________
12. $^{51}\mathrm{Cr} \rightarrow$ ____________ + ____________
13. $^{59}\mathrm{Ni} \rightarrow$ ____________ + ____________
14. $^{65}\mathrm{Zn} \rightarrow$ ____________ + ____________
15. $^{40}\mathrm{K} \rightarrow$ ____________ + ____________
16. $^{3}\mathrm{H} \rightarrow$ ____________ + ____________
17. $^{11}\mathrm{C} \rightarrow$ ____________ + ____________
18. $^{18}\mathrm{F} \rightarrow$ ____________ + ____________
19. $^{110}\mathrm{Ag}^{m} \rightarrow$ ____________ + ____________
20. $^{110}\mathrm{Ag} \rightarrow$ ____________ + ____________

DATA TABLE 1-5-4

RADIOACTIVE DECAY SCHEMES

1. ${}^{6}_{2}\mathrm{He}$

2. ${}^{60}\mathrm{Co}$, ${}^{60}\mathrm{Co}^{m}$

3. ^{131}I

4. ^{137}Cs

5. ^{210}Po

6. ^{196}Au

7. ^{133}Ba

8. ^{54}Mn

9. ^{22}Na

10. $^{99}Tc^{m}$

REFERENCE MATERIALS

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TEST

1. Which of the following statements about alpha particles are true? Circle the letter of each true statement.

   a. Alpha particles are a form of electromagnetic radiation.
   b. Alpha particles are emitted at speeds from 1.6×10^5 to 1.6×10^6 cm/sec.
   c. Alpha particles carry two units of positive electrical charge.
   d. Because of their size and relatively slow speed, alpha particles can travel only a few centimeters in air.
   e. Alpha particles are ionized hydrogen nuclei.
   f. Alpha particles are usually ejected with natural disintegration of radioactive nuclei of various heavy elements.

2. Which of the following statements about beta particles are true? Circle the letter of each true statement.

   a. Beta particles originate in the nucleus of an atom.
   b. A beta particle has greater mass than a proton.
   c. Beta particles are emitted at velocities approaching the speed of light.
   d. In certain nuclear transformations, beta particles have a positive charge and are called positrons.
   e. Beta particles have a range of several miles in air.
   f. Beta particles are electrons.

3. Nine decay schemes are drawn on the next two pages. Five of these schemes are correct. Identify each correct scheme by placing the letter of the drawing in the spaces below.

   Correct Scheme: ______

   Correct Scheme: ______

   Correct Scheme: ______

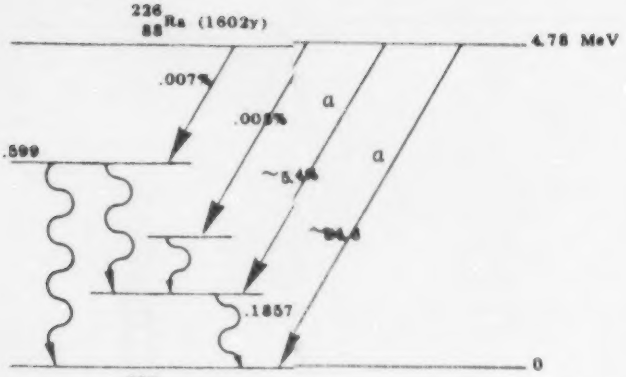
   Correct Scheme: ______

   Correct Scheme: ______

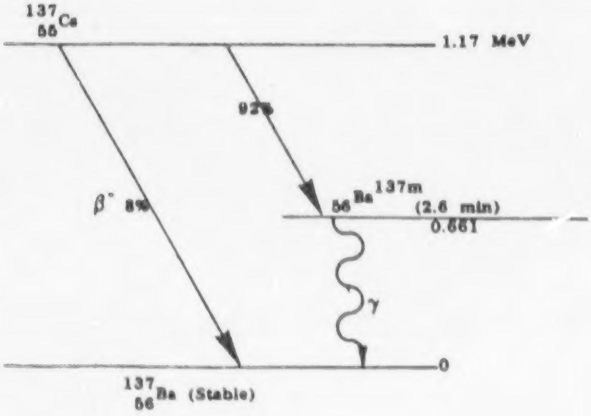
Circle the letter of the best response to complete the definition to 4 and 5.

4. Electromagnetic energy emanating from the nucleus of an atom.

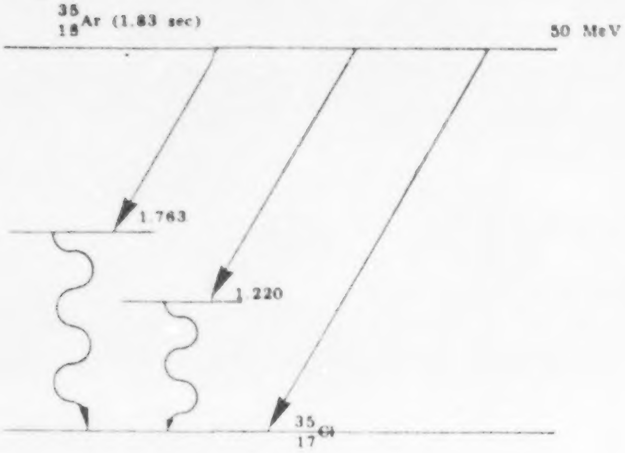
   a. beta emissions
   b. gamma radiation
   c. isomers
   d. K capture


$^{226}_{88}$Ra (1602y)
4.78 MeV
.007%
.006%
a
a
~5.4%
~94.6
.599
.1857
0
$^{222}_{86}$Rh (3.82d)

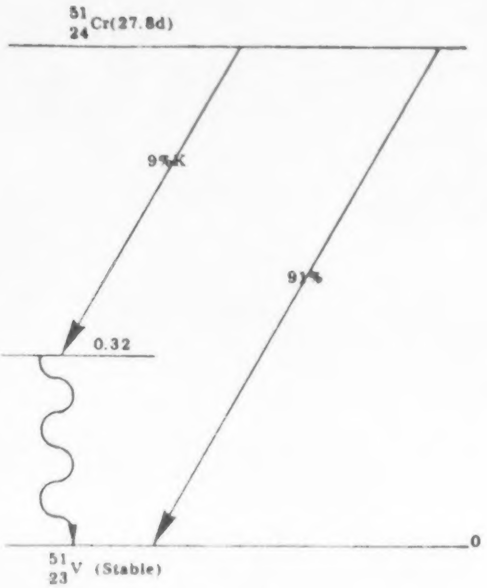
DRAWING A


$^{137}_{55}$Cs
1.17 MeV
92%
β^- 8%
$^{137m}_{56}$Ba
(2.6 min)
0.661
γ
0
$^{137}_{56}$Ba (Stable)

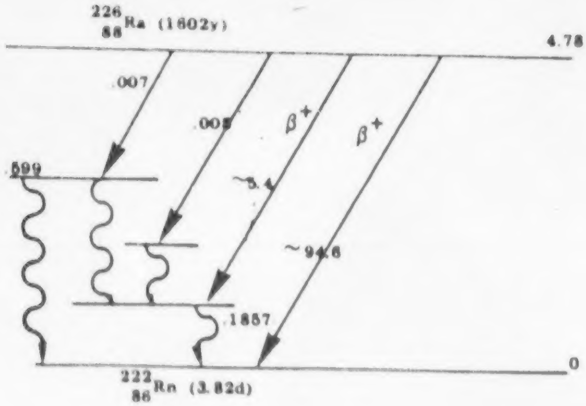
DRAWING B


$^{35}_{18}$Ar (1.83 sec)
50 MeV
1.763
1.220
$^{35}_{17}$Cl

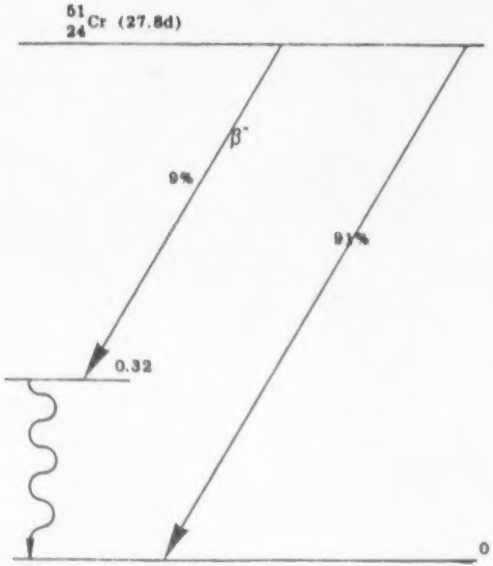
DRAWING C


$^{51}_{24}$Cr(27.8d)
9% K
91%
0.32
0
$^{51}_{23}$V (Stable)

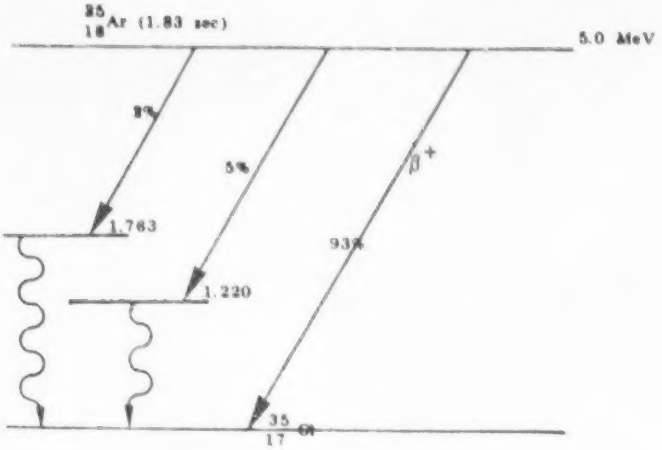
DRAWING D


226 88 Ra (1602y)
4.78 MeV
.007
.005
β+
β+
~5.4
~94.6
.599
.1857
0
222 86 Rn (3.82d)

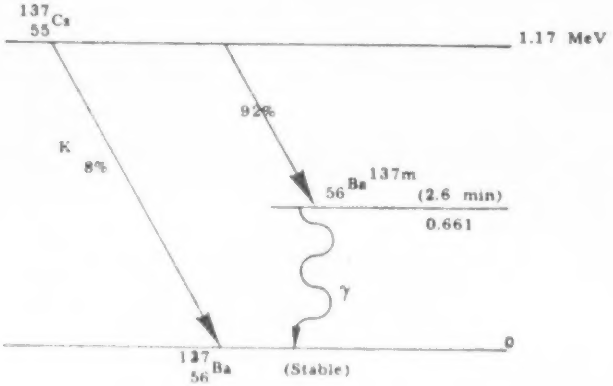
DRAWING E


51 24 Cr (27.8d)
β-
9%
91%
0.32
0
51 23 V
(Stable)

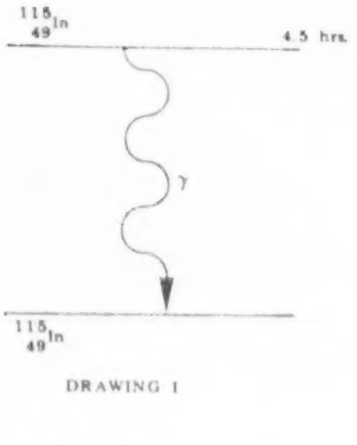
DRAWING G


35 18 Ar (1.83 sec)
5.0 MeV
2%
5%
β+
93%
1.763
1.220
35 17 Cl

DRAWING F


137 55 Cs
1.17 MeV
92%
K
8%
56 Ba 137m
(2.6 min)
0.661
γ
0
137 56 Ba
(Stable)

DRAWING H


115 49 In
4.5 hrs.
γ
115 49 In

DRAWING I

5. Bundles of electromagnetic energy are:

   a. protons
   b. neutrons
   c. alpha particles
   d. photons

6. Given the following decay process equations, write in the blanks the missing term needed to complete the decay process.

   a. $^{205}_{82}\text{Pb} \longrightarrow \_\_\_\_\_\_ + ^{205}_{82}\text{Pb}$

   b. $^{112}_{47}\text{Ag} \longrightarrow \_\_\_\_\_\_ + ^{112}_{48}\text{Cd}$

   c. $^{41}_{20}\text{Ca} + \_\_\_\_\_\_ \longrightarrow ^{41}_{19}\text{K}$

   d. $^{210}_{84}\text{Po} \longrightarrow \_\_\_\_\_\_ + ^{206}_{82}\text{Pb}$

   e. $^{192}_{80}\text{Hg} \longrightarrow \_\_\_\_\_\_ + ^{192}_{79}\text{Au}$

   f. $^{116}_{49}\text{In} \longrightarrow \_\_\_\_\_\_ + ^{116}_{49}\text{In}$

   g. $^{39}_{20}\text{Ca} \longrightarrow \_\_\_\_\_\_ + ^{39}_{19}\text{K}$

7.

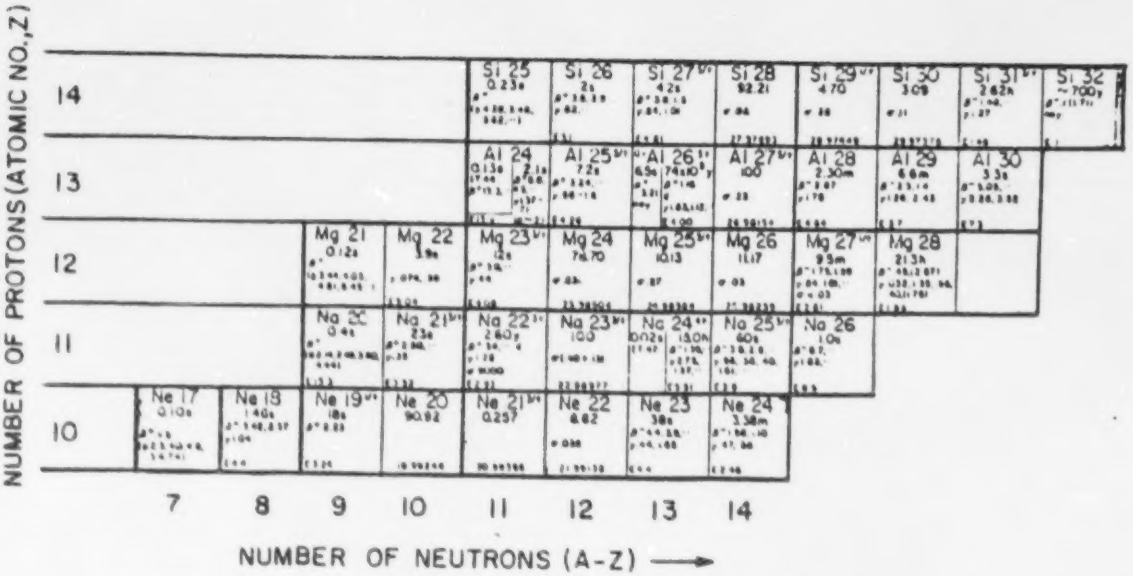


Figure 1-5-13. A Portion of the Chart of the Nuclides

Locate Aluminum-28 on the chart above and answer these questions about it.

a. How many neutrons? ______

b. How many protons? ______

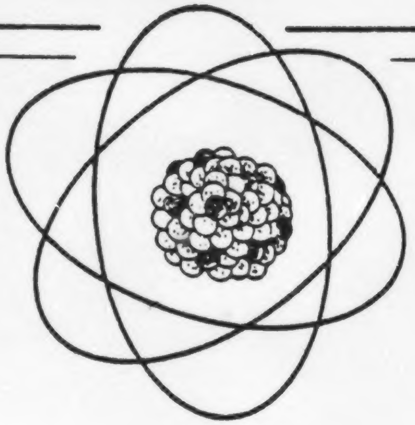
c. Is Aluminum-28 stable or radioactive? ______________

d. If it is radioactive, gives its half-life. __________

e. If it is radioactive, give its decay mode. __________

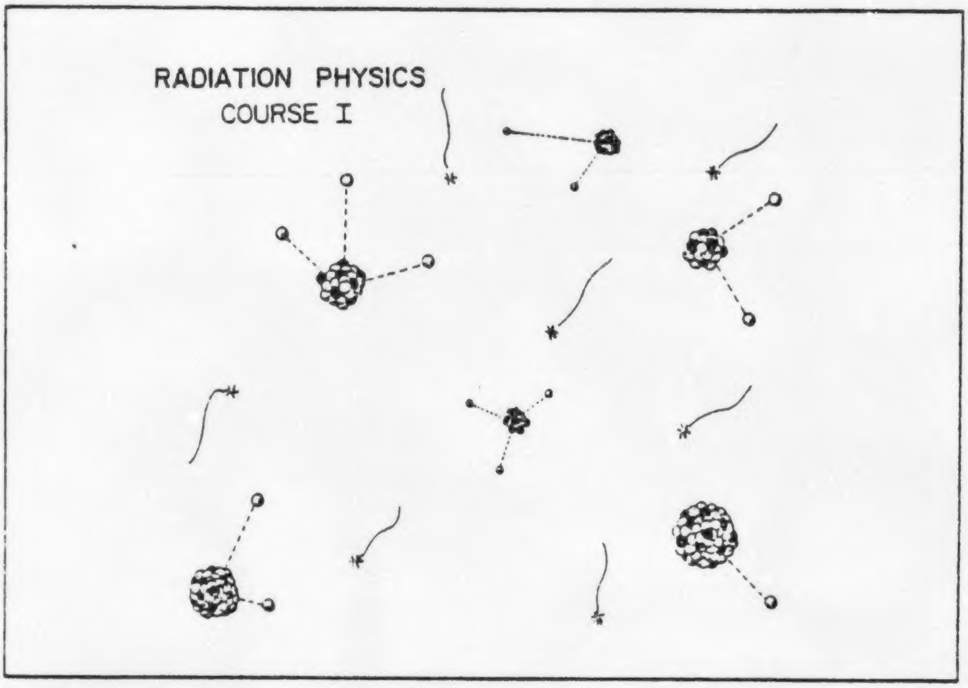
f. If Aluminum-28 is radioctive, give the average energy for each decay mode. β __________, γ__________

g. If Aluminum-28 is stable, what is its abundance? ______________



NUCLEAR TECHNOLOGY

MODULE 1-6 BASIC PROPERTIES OF GAMMA RADIATION


RADIATION PHYSICS
COURSE I

COURSE MODULES

COURSE 1 RADIATION PHYSICS

	MODULE 1-1	Introduction to Radiation Laboratory Safety
	MODULE 1-2	Basic Radiation Detection and Measuring Equipment
	MODULE 1-3	Atomic Structure and Radioactivity
	MODULE 1-4	Radioactive Decay and Half-life
	MODULE 1-5	Decay Processes and Schemes
⇨	MODULE 1-6	Basic Properties of Gamma Radiation

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Module 1-5, "Radioactive Decay Processes and Schemes," introduced the student to different types of emission (alpha, beta and gamma) that result from radioactive decay. Alpha and beta radiations were identified as particles; gamma radiation was described as a type of electromagnetic radiation similar to radio and TV waves, visible light and x-rays.

The basic properties of gamma radiation, including properties common to all electromagnetic radiation, are discussed in this module under two main topics:

Reduction of gamma radiation intensity with distance from a point source (inverse-square law).

Exponential reduction of gamma ray intensity caused by absorbing material interposed between the radioactive source and a detector.

Both of these types of reduction (attenuation) are important considerations of radiation safety, especially in reducing radiation exposure.

Basic properties of alpha and beta radiation are deferred to a later course.

MODULE PREREQUISITES

The student should be familiar with and practice basic radiation safety, approved laboratory procedures and know how to use a GM scaler-ratemeter.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Perform the following tasks concerning the properties of gamma radiation:
    a. Define the following:
        Electromagnetic radiation.
        Inverse-square law.
        Frequency.
        Wavelength.
        Linear absorption coefficient.
        Mass absorption coefficient.
        X-rays.
        Monoenergetic.
    b. List at least six designations of electromagnetic radiation.
    c. State two similarities and differences between gamma radiation and x-rays.
    d. Sketch a wave pattern; label wavelength and amplitude. State algebraic relationship between frequency and wavelength of electromagnetic radiation.

e. Write an explanation of the equation that relates linear absorption coefficient to mass absorption coefficient.

f. Calculate the fraction of radiation absorbed in a given material of known thickness and composition. (Be able to work problem by using either a linear or a mass absorption coefficient.)

g. Find energy of a narrow beam, monoenergetic gamma radiation after passage through a material of known thickness and composition. (Be able to work problem by using either a linear or a mass absorption coefficient.)

2. Given the appropriate equipment and necessary data, perform the following tasks related to gamma ray absorption in matter:

a. Obtain data on gamma count-rate versus absorber thickness by varying absorber thickness; use both an aluminum and a lead abosrber.

b. Plot data on semilog graph paper (distance along abscissa), and draw "best fit" straight lines through data.

c. Determine linear and mass absorption coefficients, and compare with standard values.

d. Determine half-value layers (half-thicknesses).

3. Given the appropriate equipment, perform the following tasks related to inverse-square law variation of intensity of gamma radiation with distance from a gamma source:

a. Obtain data on gamma count-rate versus distance by varying distance between gamma source and probe (detector).

b. Plot data on log-log graph paper (distance along abscissa), and draw straight line "best-fit" through data.

c. Calculate decrease in intensity, based on inverse-square law. Determine extent to which experimental data differs from that predicted by inverse-square law. Explain differences, if any.

d. Show graphically that gamma radiation intensity decreases according to the inverse-square law (considering that radiation emits from a point source).

ELECTROMAGNETIC RADIATION

Many phenomena in nature are periodic; that is, they repeat themselves in some predictable way. Many periodic disturbances, such as musical sounds, human speech, the swing of a pendulum, a cork bobbing up and down in the water, the violent shock from an earthquake, may be represented by waves, or wavelike motions. Light, as it travels through space, can also be described as a wave phenomenon.

For all wave phenomena, the disturbance at a particular place recurs or repeats itself many times in a certain length of time. The actual number of times it recurs per second is called the frequency of the wave. For example, alternating current available in the continental United States has a normal frequency of 60 cycles (vibrations) each second. One cycle per second is commonly called a Hertz (Hz).

What are some of the characteristics of a wave?

The amplitude of a wave starts from some zero point (Figure 1-6-1), builds to a maximum value, falls back to zero, builds to a maximum in the opposite direction and returns to zero. This process repeats itself.

The distance over which a wave repeats itself - the physical length of a complete cycle of the wave - called a wavelength, λ*. The time over which the wave repeats it-

---

* The symbol, λ (lambda) denotes both wavelength and decay constant. The two terms should not be confused, however.

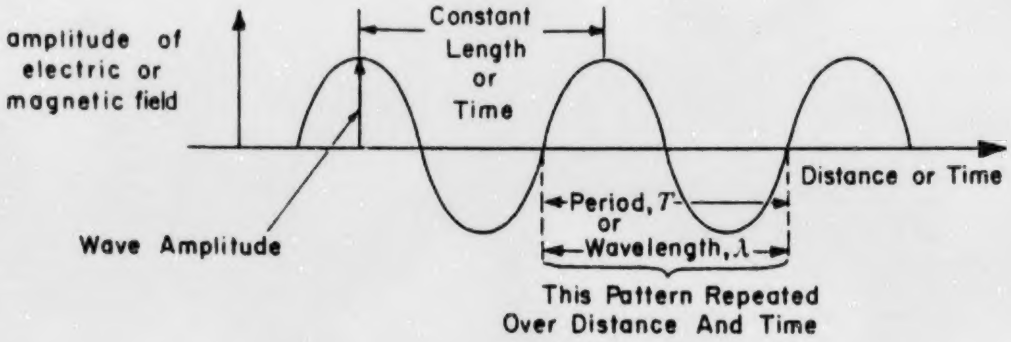

amplitude of electric or magnetic field
Constant Length or Time
Distance or Time
Period, T
or
Wavelength, λ
Wave Amplitude
This Pattern Repeated Over Distance And Time

Figure 1-6-1. A repeating wave pattern.

self is called a period. The amplitude (height) of a wave is its maximum displacement from an equilibrium or zero position.

It should be noted, too, that waves repeat themselves in both space and time as they travel through space (Figure 1-6-1).

The number of complete vibrations or oscillations per unit time is defined as the wave frequency, ν (pronounced "new"). For example, someone sends a wave along a piece of rope by moving one end of the rope up and down. If the end of the rope is moved at the rate of 5 cycles each second, the frequency of the mechanical wave sent down the rope will be 5 Hertz.

Suppose the wavelength produced along the rope is 10 centimeters (the distance between any two successive crests or successive troughs of the wave), how fast is the wave moving? If it is advancing at a rate of 5 cycles per second and the length of each wave is 10 centimeters, then velocity, v, of the wave may be calculated as follows:

velocity = (frequency) (wavelength)

or $v = \nu \times \lambda$ Equation 1-6-1
(Equation = Eq.)

where:

ν = wave frequency (Hertz).
λ = wavelength (meters or centimeters).

Therefore,

ν = (5 Hz) (10 cm)
λ = 50 cm/sec.

Light, moving through space, belongs to a special class of waves called electromagnetic (em) waves. An em wave actually consists of two waves, one electric and the other magnetic in character, perpendicular to one another, moving through space at the speed of light.

Each em is also an example of a transverse wave. The amplitude of a transverse wave is perpendicular to its direction of propagation.

Electromagnetic waves include radio (and TV) waves, microwaves, x-rays, gamma rays, as well as a narrow band of frequencies called "light." All em waves have the same basic nature and properties; however, they differ in frequency (wavelength) and intensity (Figure 1-6-2).

The entire span of frequencies is generally referred to as the electromagnetic spectrum.

It should be emphasized that, in the transmission and

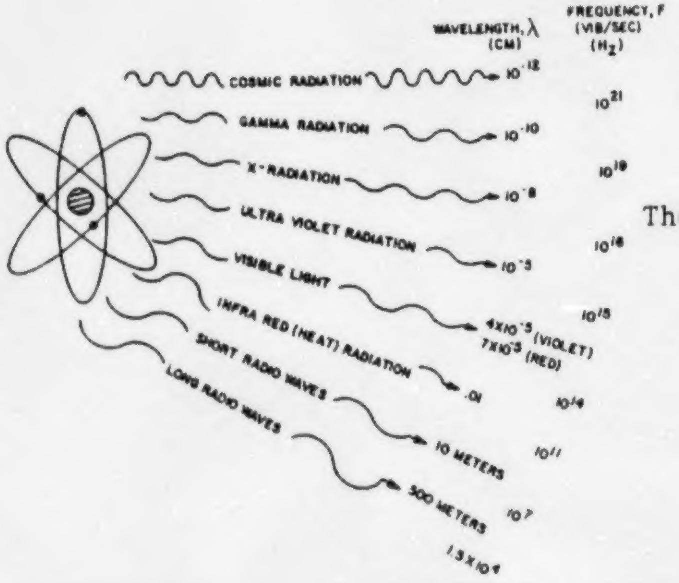

WAVELENGTH, λ (CM)
FREQUENCY, F (VIB/SEC) (H_Z)
COSMIC RADIATION
10^{-12}
10^{21}
GAMMA RADIATION
10^{-10}
10^{19}
X-RADIATION
10^{-8}
ULTRA VIOLET RADIATION
10^{16}
10^{-5}
VISIBLE LIGHT
10^{15}
4×10^{-5} (VIOLET)
7×10^{-5} (RED)
INFRA RED (HEAT) RADIATION
.01
10^{14}
SHORT RADIO WAVES
10 METERS
10^{11}
LONG RADIO WAVES
500 METERS
10^{7}
1.5×10^{4}

Figure 1-6-2.
The electromagnetic spectrum.

reception of electromagnetic radiation, the frequency of a particular em wave generally determines the types of generating, transmitting and receiving devices used. Radio frequency transmitters and receivers, operating over frequency ranges of 10^3 to 10^6 Hz, use components quite different from those used for generating and detecting light waves. The latter must operate at frequencies on the order of 10^{14} Hz.

All electromagnetic waves, regardless of frequencies, have been found, experimentally, to travel at the same speed (c) in a vacuum, where $c \approx 3 \times 10^8$ meters/sec:

$$\text{Velocity} = (\text{frequency})\ (\text{wavelength})$$
$$c = \nu \times \lambda.$$

ν = frequency (Hz).

λ = wavelength (meters).

For example, a gamma ray (photon) has a wavelength of about 10^{-11} meters.

EXAMPLE

GIVEN: $\lambda = 10^{-11}$ meters.

$c = 3 \times 10^{8}$ meters/sec.

FIND: Frequency, ν, of vibration of a gamma photon.

SOLUTION:

$$c = \nu \times \lambda$$

$$\nu = c/\lambda = \frac{3 \times 10^{8} \text{ meters/sec}}{10^{-11} \text{ meters}}$$

$$\nu = 3 \times 10^{19} \text{ sec}^{-1}$$

$$\nu = 3 \times 10^{19} \text{ Hz.}$$

NOTE: Electric and magnetic forces are oscillating at a rate of 3×10^{19} times each second.

What makes em waves so useful?

All types of waves, whether mechanical or electromagnetic in origin, carry energy. Transportation and fine control of energy over some distance is of great importance in many applications. Electromagnetic waves incorporate these two characteristics (e.g., a radio wave, which may transport a message millions of miles through space to a tiny antenna moving rapidly away from Earth.)

ATTENUATION (OR ABSORPTION) BY MATTER

As stated in the previous section, gamma radiation is a type of electromagnetic radiation. Because of this fact, basic properties of gamma radiation are markedly different from those of charges particles, such as alpha and beta particles. Gamma rays and x-rays (also a type of electromagnetic radiation) show a characteristic exponential absorption in matter and have no definite range such as that found for beta or alpha particles.

Charged particles lose most of their energy during the course of a large number of collisions with atoms. The energy loss occurs in many small steps, and the particle gradually slows down until it is stopped altogether. When a beam of gamma rays is incident on an absorber, each photon removed from the beam is removed individually in a single event. This "one-shot," random removal process is responsible for the exponential absorption.

Alpha rays are completely stopped by a few centimeters of air or a sheet or two of paper. Beta rays are stopped by a few meters of air or a few millimeters of lead. Some gamma rays, however, can penetrate the most dense materials, since only a certain fraction are removed per unit length of travel through the material.

LINEAR ABSORPTION COEFFICIENT

Gamma rays are diminished in number by any given absorber, but are not wholly stopped. If the number of monoenergetic* gamma photons traversing an absorber is plotted against the thickness of the absorber, an exponential curve results. The intensity (I) of the gamma rays after passing through an absorber of thickness x may be calculated from Equation 1-6-2:

$$I = I_o e^{-\mu x} \qquad \text{Eq. 1-6-2}$$

where

I_o = initial intensity of gamma rays in units of $\frac{\text{energy}}{(\text{area})(\text{time})}$.

e = base of natural logarithms.

μ = linear absorption coefficient of absorber for given gamma rays in reciprocal centimeters.

For the exponent to be dimensionless, μ and x must have reciprocal units; if μ is in cm^{-1} units, then x must be in cm units.

Note: This equation is of the same form as that for radioactive decay, which, in Module 1-4, "Radioactive Decay and Half-Life," was given as $N = N_o e^{-\lambda t}$ or $A = A_o e^{-\lambda t}$. In each equation, the variable decreases exponentially, whether it be number of atoms, activity or intensity.

---

* "Monoenergetic" means that all gamma rays have one (or the same) energy. All gamma rays considered in this discussion are assumed to be monoenergetic, even though gamma rays are generally of different energies. The effect of a "spread" of energies will be studied later.

EXAMPLE

Lead Absorber

Given: (From Figure 1-6-3)

$\mu = 0.80 \text{ cm}^{-1}$ for 1 MeV γ-rays in lead:

$x = 0.25 \text{ inch} \times 2.54 \frac{\text{cm}}{\text{inch}} = 0.64 \text{ cm}$.

Find: Fraction of gamma rays that pass through $(\frac{I}{I_o})$.

Solution:

$$I = I_o e^{-\mu x} = I_o e^{-(0.80)(0.64)} = I_o e^{-(0.51)}$$

$$\frac{I}{I_o} = e^{-(0.51)} = 0.60$$

$$\frac{I}{I_o} = 0.60.$$

About 60% pass through 1/4 inch of lead. The other 40% either are absorbed or scatter out of the beam.

Aluminum Absorber

Given: (From Figure 1-6-3)

$\mu = 0.16 \text{ cm}^{-1}$ for 1.0 MeV γ-rays in aluminum:

$x - 0.64 \text{ cm}$.

Find: $\frac{I}{I_o}$.

Solution:

$$\frac{I}{I_o} = e^{-\mu x} = e^{(-0.16 \text{ cm}^{-1}) \times (0.64 \text{ cm})}$$

$$\frac{I}{I_o} = e^{-(0.10)}$$

$$\frac{I}{I_o} = 0.90.$$

90% pass through the same thickness of aluminum; only 10% are removed from the beam. Clearly, lead is a better absorber (attenuator) than aluminum for 1.0 MeV γ-rays.

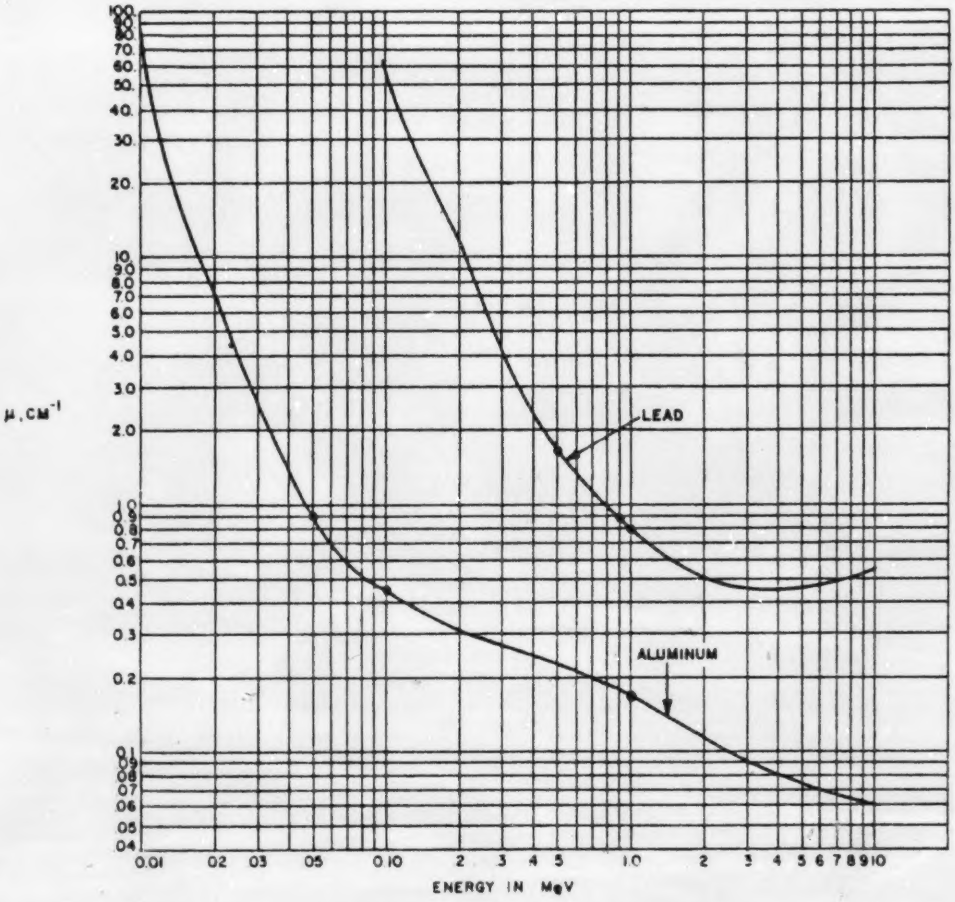


Figure 1-6-3. Linear absorption coefficients (μ) for x-ray and gamma radiation in aluminum and lead.

The linear absorption coefficients (μ) of absorbers for given gamma ray energies (such as those given for lead and aluminum in Figure 1-6-3) can be obtained from graphs in many manuals and textbooks.

Absorber thicknesses (areal densities) are usually expressed in units of g/cm^2 or mg/cm^2. To convert to thicknesses in cm, divide by density:

$$\text{Thickness (cm)} = \frac{\text{areal density } (mg/cm^2)}{\text{volume density } (mg/cm^3)} .$$

Eq. 1-6-3

To calculate the thickness of aluminum (with a density of 2.70 gram/cm^3 = 2700 mg/cm^3):

$$\text{Thickness (cm)} = \frac{\text{areal density } (mg/cm^2)}{2700 \ (mg/cm^3)} .$$

To calculate the thickness of lead (with a density of 11/34 gm/cm^3 = 11340 mg/cm^3):

$$\text{Thickness (cm)} = \frac{\text{areal density } (mg/cm^2)}{11340 \ (mg/cm^3)}$$

Recall that decay constant λ in the formula, $A = A_0 e^{-\lambda t}$, count be determined from a semilog plot of activity versus time. Similarly, linear absorption coefficient (μ) can be determined from a semilog plot of gamma intensity versus absorber thickness.

The formula, $I = I_o e^{-\mu x}$ (Figure 1-6-4), can be rearranged as follows:

$$\frac{I}{I_o} = e^{-\mu x}. \qquad \text{Eq. 1-6-4}$$

By taking the natural log of both sides, this equation becomes:

$$\ell n\ (\frac{I}{I_o}) = \ell n\ (e^{-\mu x}) = -\mu x.$$

This expreseion can be solved for μ:

$$\ell n\ (\frac{I}{I_o}) = -\mu x$$

$$\mu = -\frac{1}{x}\ \ell n\ (\frac{I}{I_o}) = \frac{1}{x}\ \ell n\ (\frac{I_o}{I})$$

where: $\ell n\ (\frac{I}{I_o}) = -\ell n\ (\frac{I_o}{I})$.

Knowledge of μ, the linear absorption coefficient determined from Equation 1-6-4 or a graph (Figure 1-6-4) can be used to determine the approximate energy of an unknown radionuclide. After determining linear absorption coefficient μ, the coefficient can be located on an appropriate

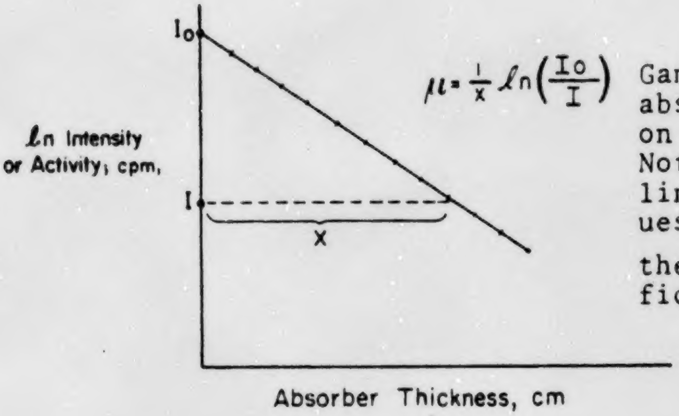


Figure 1-6-4. Gamma-ray intensity versus absorber thickness plotted on a semilogarithmic graph. Note: plot is a straight line, and corresponding values of I_o/I and x lead to the linear absorption coefficient, μ.

μ versus energy curve, then, corresponding energy can be determined (Figure 1-6-5). Be sure to use correct absorption curve for each material.

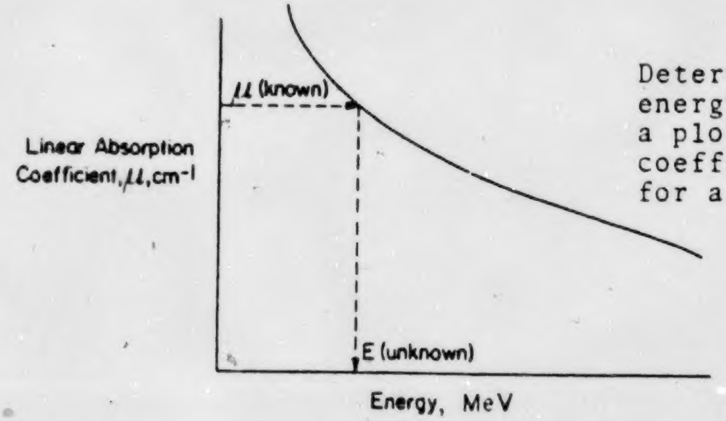


Figure 1-6-5. Determination of unknown energy of gamma ray from a plot of linear absorption coefficient versus energy for a given absorber.

EXAMPLE

Given:

$x = 0.10 \text{ inch} - 0.10 \text{ inch} \times 2.54 \frac{\text{cm}}{\text{inch}} = 0.254 \text{ cm}.$

$\frac{I}{I_o} = 0.50.$

Find: μ and energy, E.

Solution:

$\frac{I}{I_o} = e^{-\mu x}$

$0.50 = e^{-0.254 \mu}.$

Take natural log of both sides:

$(0.50) = \ln e^{-0.254 \mu}$

$-0.693 = 0.254\mu$

$\mu = \frac{0.693}{0.254 \text{ cm}} = 2.73 \text{ cm}^{-1}.$

(From Figure 1-6-3) energy corresponding to $\mu = 2.73 \text{ cm}^{-1}$ for aluminum is 0.031 MeV.

MASS ABSORPTION COEFFICIENT

Mass absorption coefficient is obtained by dividing a linear absorption coefficient by absorber density:

$$\mu_m = \frac{\mu}{\rho} \qquad \text{Eq. 1-6-5}$$

where

μ_m = mass absorption coefficient, $\frac{cm^3}{gram}$.

μ = linear absorption coefficient, $\frac{1}{cm}$.

ρ = absorber density, $\frac{gram}{cm^3}$.

The mass absorption coefficient, $\mu_m \frac{cm^3}{gram}$, varies with gamma or x-ray energy, as does the linear absorption coefficient; however, at any given energy level, particularly in the 0.2 MeV or 3.0 MeV range, mass absorption coefficients for different absorbing materials are approximately the same.

Equation 1-6-2 may be rewritten in terms of mass absorption coefficient as follows:

$$I = I_o e^{-(\mu)x} = I_o e^{-\mu_m \rho x}$$

$$I = I_o e^{-\mu_m \rho x} .$$

Values for μ_m for lead and aluminum absorbers are given in Figure 1-6-6. The density of lead is 11.34 gram/cm^3, and that of aluminum is 2.70 gram/cm^3. Values of μ_m and ρ for other absorbers are given in the Radiological Health Handbook.

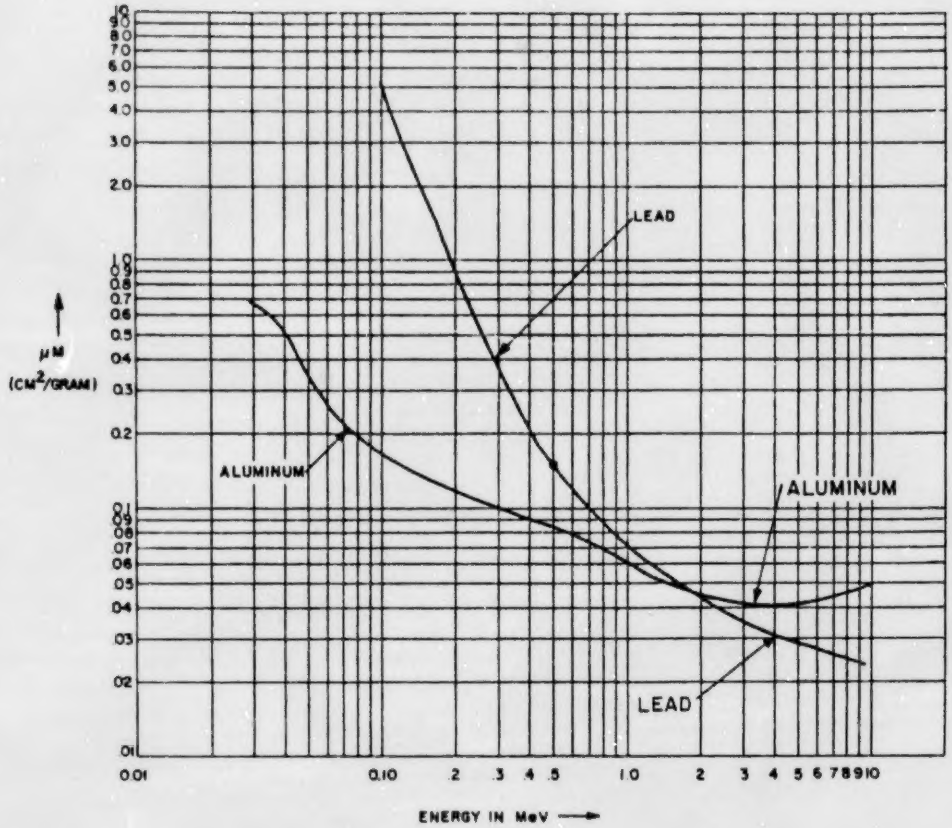


Figure 1-6-6. Total mass absorption coefficients (μ_m) for x- and gamma radiation in aluminum and lead. (From Radiological Health Handbook.)

EXAMPLE

Given:

$x = 0.30 \text{ inch} = 0.30 \text{ inch} \times 2.54 \frac{\text{cm}}{\text{inch}} = 0.762 \text{ cm}:$

$\frac{I}{I_o} = 0.50.$

Find: μ and energy, E.

Solution:

$$\frac{I}{I_o} = e^{-\mu x}$$

$$0.50 = e^{-\mu x}$$

$$\ln(0.50) = (-\mu)(0.762)$$

$$-0.693 = -0.762\mu$$

$$\mu = \frac{0.693}{0.762}$$

$\mu = 0.91\ cm^{-1}$.

(From Figure 1-6-3) energy corresponding to $\mu = 0.91$ cm for lead is 0.88 MeV.

EXAMPLE

Given:

Energy = 0.5 MeV.

$x = 0.5$ cm.

$\rho = 11.34\ gm/cm^3$.

Find: μ, I/I_o.

Solution:

(From Figure 1-6-6) $\mu_m = 0.15\ cm^2/gram$.

(From Figure 1-6-3) $\mu = 1.70\ cm^{-1}$.

Also, μ can be calculated from the relation:

$\mu = \rho\mu_m$.

Thus, $\mu = 11.34\ \frac{gm}{cm^3}\ 0.15\ \frac{cm^2}{gm} = 1.70\ cm^{-1}$

For I/I_o:

$$\frac{I}{I_o} = e^{-\mu x} = e^{-(1.70\ \text{cm}^{-1})}\ x\ 0.5\ \text{cm}$$

$$\frac{I}{I_o} = e^{-(0.85)}$$

$$\frac{I}{I_o} = 0.427.$$

EXAMPLE

Given:

Energy = 0.1 MeV.

x = 0.1 cm.

ρ = 2.70 gm/cm^3.

Find: μ_m, μ, $\frac{I}{I_o}$.

Solution:

(From Figure 1-6-6) μ_m = 0.17 cm^2/gram.

(From Figure 1-6-3) μ = 0.46 cm^{-1}.

$$\frac{I}{I_o} = e^{-\mu x} = e^{-0.46\ \text{cm}^{-1}\ x\ 0.1 \text{cm}}.$$

$$= e^{-0.046}$$

$$\frac{I}{I_o} = 0.955.$$

HALF-VALUE LAYER (HVL)

The half-value layer (HVL) of an absorbing material is defined as that thickness, x, which will reduce the intensity to half its original value (Figure 1-6-7). A half-value thickness ($x_{\frac{1}{2}}$) can be related to linear absorption coefficient as follows:

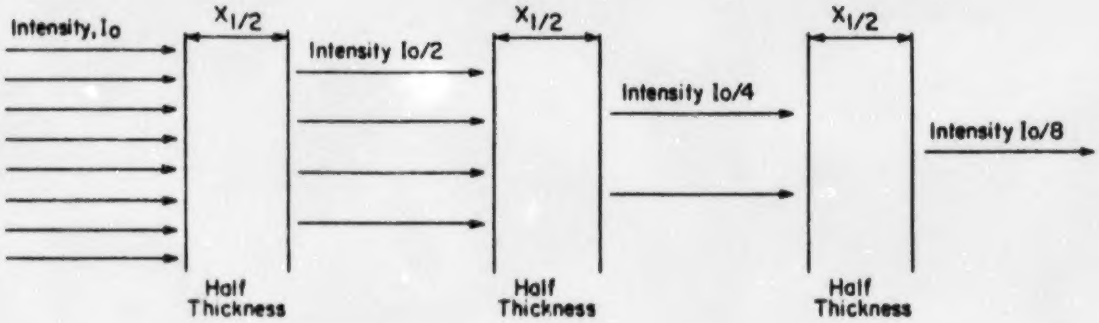

Intensity, Io
X1/2
Intensity Io/2
X1/2
Intensity Io/4
X1/2
Intensity Io/8
Half Thickness
Half Thickness
Half Thickness

Figure 1-6-7. Half-value layer for absorption of gamma rays.

Definition:

$$\text{For } \frac{I}{I_0} = \frac{1}{2},\ x = x_{\frac{1}{2}}.$$

By substituting $I = I_0 e^{-\mu x}$:

$$\frac{I}{I_0} = \frac{1}{2} = e^{-\mu x_{\frac{1}{2}}} = \frac{1}{e^{\mu x_{\frac{1}{2}}}}.$$

By inverting:

$$2 = e^{\mu x_{\frac{1}{2}}}.$$

By taking the natural log of both sides:

$$\ln(2) = \mu x_{\frac{1}{2}}.$$

By rearranging and substituting:

$$x_{\frac{1}{2}} = \frac{0.693}{\mu}. \qquad \text{Eq. 1-6-6}$$

Remember, ℓn (2) = 0.693.
Note: Both half-value layer and half-life use similar-type exponential equations (Table 1-6-1) that express reduction in intensity or activity (one by absorber thickness and one by time).

TABLE 1-6-1
SIMILARITY BETWEEN HALF-VALUE LAYER AND HALF-LIFE

	Absorption	Decay
Equation	$I = I_0 e^{-\mu x}$	$A = A_0 e^{-\lambda t}$
Independent variable	Thickness, x	Time, t
Dependent variable	Intensity, I	Activity, A
Coefficient or constant	Linear absorption coefficient, μ	Decay constant, λ
Half-value layer or half-life	Half-value layer $x_{\frac{1}{2}}$	Half-life, $T_{\frac{1}{2}}$
Fundamental relationship	$x_{\frac{1}{2}} = \frac{0.693}{\mu}$	$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$

The half-value layer concept is used frequently in the selection of absorber materials to shield against specific gamma or x-ray courses.

EXAMPLE

Given: The half-value layer of concrete is 1.0 inch. One inch of concrete reduces intensity to 1/2 the original value; two inches reduces intensity to 1/2 x 1/2 = 1/4.

Find: Thickness of concrete needed to reduce intensity of an x-ray beam to 1/64 its original intensity.

Solution: Set up a table: extrapolate to 1/64.

Thickness Inches	Fraction of Original Intensity
0	1.0
1	1/2
2	1/2 x 1/2 = 1/4
3	1/2 x 1/2 x 1/2 = 1/8
4	1/2 x 1/2 x 1/2 x 1/2 = 1/16
5	1/2 x 1/2 x 1/2 x 1/2 x 1/2 = 1/32
6	1/2 x 1/2 x 1/2 x 1/2 x 1/2 x 1/2 = 1/64

$$n \times \text{HVL} = \frac{1}{2^n}$$

Thus, six inches of concrete is needed to reduce intensity to 1/64 of its original value.

EXAMPLE

Given:

$x_{\frac{1}{2}}$ = 1.0 inch - 2.54 cm.

Find: μ.

Solution: (Use Equation 1-6-4)

$$x_{\frac{1}{2}} = \frac{0.693}{\mu}$$

(Rearrange to get)

$$\mu = \frac{0.693}{x_{\frac{1}{2}}} \frac{0.693}{2.54} = 0.273\ \text{cm}^{-1}$$

$\mu = 0.273\ \text{cm}^{-1}$.

INVERSE-SQUARE LAW

All types of radiation emitted by radioactive materials propagate outward in straight lines unless absorbed or scattered by materials in their paths. As radiation gets further from its source, intensity (radiation per unit area) is reduced because the same radiation is spread over a larger area (Figure 1-6-8

Intensity, I_1, at distance, d_1, is greater than intensity, I_2, at distance, d_2. These intensities are related by Equation 1-6-7:

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2 \qquad \text{Eq. 1-6-7}$$

$$I_1 d_1^{\,2} = I_2 d_2^{\,2}.$$

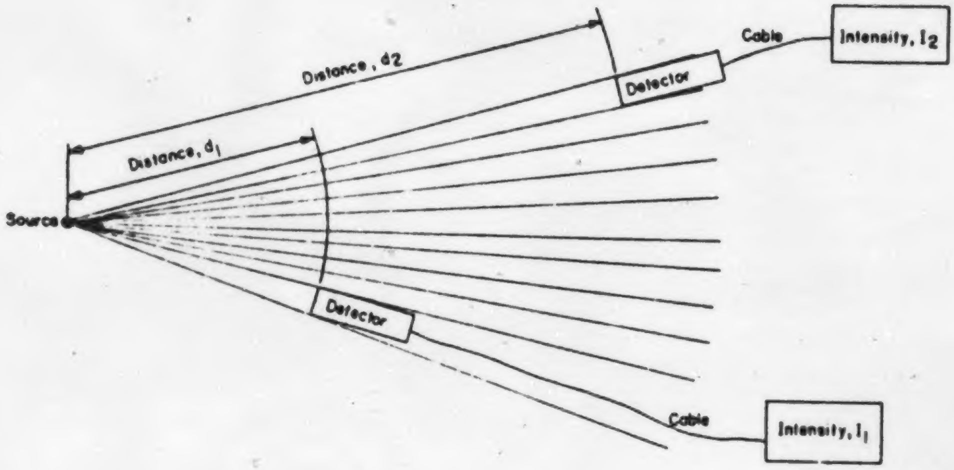

Distance, d2
Cable
Intensity, I_2
Detector
Distance, d_1
Source
Detector
Cable
Intensity, I_1

Figure 1-6-8. Variation of gamma ray intensity with distance from a point source, as measured by detectors at distances d_1 and d_2.

Radiation intensity is inversely proportional to the square of the distance from the point source, hence the name, Inverse-Square Law.

EXAMPLE

Given:

I_1 = 50 mR/hr.

I_2 = 2 mR/hr.

d_1 = 3 feet.

Find: d_2.

Solution: Rearrange Equation 1-6-7 to get:

$$\frac{d_2}{d_1} = \left(\frac{I_1}{I_2}\right)^{\frac{1}{2}}$$

$$d_2 = d_1 \left(\frac{I_1}{I_2}\right)^{\frac{1}{2}}$$

$$= 3 \text{ feet} \times \left(\frac{50 \text{ mR/hr}}{2 \text{ mR/hr}}\right)^{\frac{1}{2}}$$

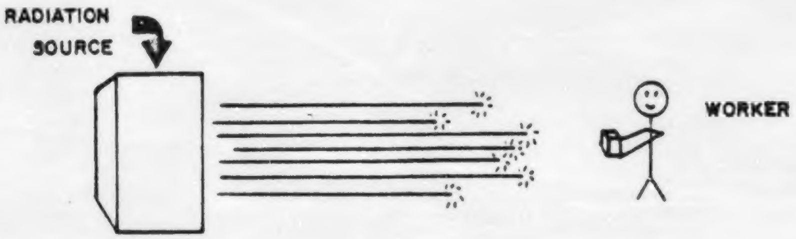
$$= 3 \text{ feet} \times (25)^{\frac{1}{2}}$$

$$= 3 \text{ feet} \times 5$$

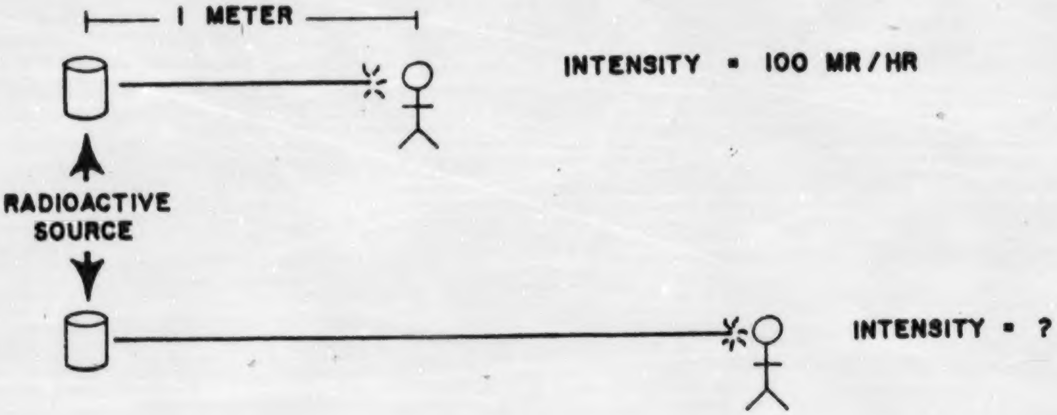
$$d_2 = 15 \text{ feet.}$$

EXERCISES

1. In the sketch below, how much material with a half-value layer (half thickness) of 2 inches, such as lead, placed between source and worker, would be required to reduce radiation in the work area to 1/8 of the present value?



2. A is standing one meter (39 in) from a point source and is being exposed at a rate of 100 mR/hr. What will be the dose rate received by A at 2 meters?


I METER
INTENSITY = 100 MR/HR
RADIOACTIVE SOURCE
INTENSITY = ?

$$I_1 d_1^2 = I_2 d_2^2$$

MATERIALS

1 Scaler-ratemeter with GM probe.
1 Set lead absorbers.
1 Set aluminum absorbers.
1 Monoenergetic gamma source, preferably ^{137}C.
1 Sample holder.
1 Ruler.
1 Ring-stand to support GM probe.
1 Sheet each, semilog and log-log graph paper (one or two cycles).

GAMMA ABSORPTION

1. Attach a GM probe to the scaler-ratemeter.
2. Turn scaler-ratemeter on; set operating voltage at value specified by instructor.
3. Record pertinent information regarding scaler-ratemeter and GM probe on Data Table 1-6-1.
4. Place the GM probe in sample holder.
5. Obtain a 10-minute background count. Record the count and count rate on the Data Table.
6. Place radioactive source on bottom shelf of sample holder; take 3-minute count; record data.
    a. Lead Absorbers.
        (1) Use lead absorber (smallest available thickness); take 3-minute count; record data; remove absorber. Absorber thickness is given in mg/cm^2.
        (2) Use lead absorber (next highest thickness); take 3-minute count; record data; remove absorber.
        (3) Continue with thicker lead absorbers until count rate is reduced to less than 25% of original.
        (4) Calculate gross count rate from data; subtract background to obtain net count rate.
        (5) Plot values of net count rate versus absorber-thickness (measured in centimeters) on semi-log paper.
        (6) Draw a best straight line through data.

(7) Determine linear and mass absorption coefficients. Show all calculations on Data Table.

(8) Obtain accepted literature values of mass absorption coefficients from instructor; calculate percentage errors.

(9) From experimental value of mass absorption coefficient, find gamma energy (from Figure 1-6-6).

(10) From experimental semilog plot of count rate versus absorber-thickness, determine half-value layer.

(11) From experimental value of mass absorption coefficient, calculate half-value layer.

b. Aluminum Absorbers.

(1) Use aluminum absorber (smallest available thickness); take 3-minute count; record data; remove absorber. Absorber thickness is given in mg/cm^2. Calculate thickness in cm and record answer on the Data Table. (Density of aluminum is 2.70 $gram/cm^3$).

(2) Repeat items 2 through 11 under a (above) substituting aluminum for lead absorbers.

INVERSE-SQUARE LAW

1. Attach GM probe to scaler-ratemeter.
2. Turn scaler-ratemeter on; set operating voltage at value specified by instructor.

3. Record pertinent information regarding scaler-ratemeter and GM probe on Data Table 1-6-2.
4. Obtain 10-minute background count; record count and count rate.
5. Set GM probe in ring stand; place radioactive source on table as shown in Figure 1-6-9.

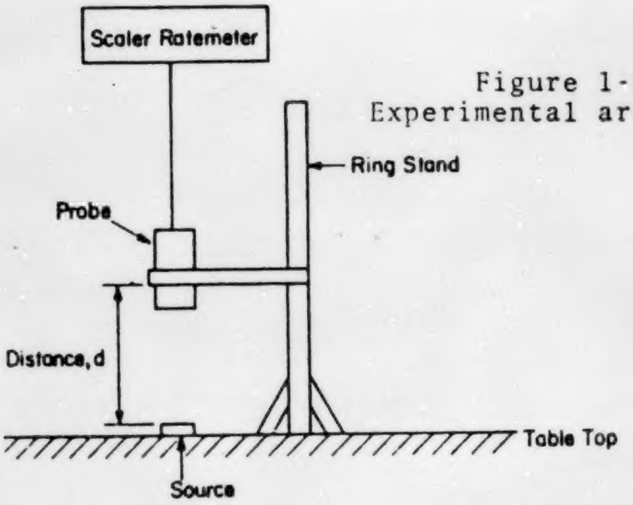


Figure 1-6-9.
Experimental arrangement.

6. Set probe so that distance, d, is 2 inches (use a ruler for this measurement). Take one-minute count; record count rates (gross and net) and distance.
7. Continue to procedure in item 6, increasing distance by one inch each time, until probe reaches top of ring stand.
8. Plot data on log-log graph paper (use net count rate as ordinate and distance as abscissa).
9. Draw best straight line through data.

10. Calculate count rate decrease with distance; use Inverse-Square Law as follows:

From log-log graph, pick count rate from straight line that corresponds with 2 inches. Let I = this count rate, and d = 2.

From the equation,

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2$$

calculate count rate for each succeeding inch; enter answers on Data Table.

Plot calculated data on log-log graph.

What can be said about calculated data? What can be said about experimental data? (Write on Data Table.)

DATA TABLE 1-6-1

GAMMA ABSORPTION

Scaler-ratemeter identification ______

GM probe identification ______

Operating voltage ______

Background count (10 minutes) ______

Radioactive source ______

Activity (curies) ______

Date of calculation ______

a. Lead Absorbers

Absorber Thickness			Gross	Net
mg/cm^2	cm	3-min Count	Count Rate	Count Rate

Linear absorption coefficient: $\mu = \frac{1}{x} \ln \left(\frac{I_o}{I}\right)$

x = ________________

I_o = ________________

I = ________________

μ = ________________

Mass absorption coefficient: $\mu_m = \frac{\mu}{\rho}$

ρ (density) = ________________

μ_m = ________________

Percentage error:

μ_m = ________________ (literature value).

$$\text{Error} = \frac{(\mu_m)\ \text{calc} - (\mu_m)\ \text{given}}{(\mu_m)\ \text{given}} \times 100\% =$$

$$\frac{(\qquad) - (\qquad)}{(\qquad)} \times 100\% = \underline{\qquad\qquad}\%.$$

Gamma energy = ________________ (Figure 1-6-6).

Half-value layer = ________________ (experimental plot).

Half-value layer = ________________ ($x_{\frac{1}{2}} = 0.693/\mu$).

b. Aluminum Absorbers

Absorber Thickness		3-min Count	Gross Count Rate	Net Count Rate
mg/cm^2	cm			

Linear absorption coefficient: $\mu = \frac{1}{x} \ell n \left(\frac{I_o}{I}\right)$

x = ____________

I_o = ____________

I = ____________

μ = ____________

Mass absorption coefficient: $\mu_m = \frac{\mu}{\rho}$

ρ (density) = ________________

μ_m = ________________

Percentage error:

μ_m = ________________ (literature value).

$$\text{Error} = \frac{(\mu_m)\ \text{calc} - (\mu_m)\ \text{given}}{(\mu_m)\ \text{given}} \times 100\% =$$

$$\frac{(\qquad) - (\qquad)}{(\qquad)} \times 100\% =$$ ________________%.

Gamma energy = ________________ (Figure 1-6-6).

Half-value layer = ________________ (experimental plot).

Half-value layer = ________________ ($x_{\frac{1}{2}} = 0.693/\mu$).

DATA TABLE 1-6-2

INVERSE-SQUARE LAW

Scaler-ratemeter identification ____________________

GM probe identification ____________________

Operating voltage ____________________

Background count (10 minutes) ____________________

Background count-rate ____________________

Radioactive source ____________________

Date of calibration ____________________

Activity (curies) ____________________

Distance Above Source	Gross Count Rate	Net Count Rate

* Inverse-Square Law Calculations:

distance, d_2	Intensity, I_2	
2 inches	__________	(from log-log plot)
3	__________	(from calculation)
4	__________	(from calculation)
5	__________	(from calculation)
6	__________	(from calculation)
7	__________	(from calculation)
8	__________	(from calculation)
9	__________	(from calculation)
10	__________	(from calculation)
11	__________	(from calculation)
12	__________	(from calculation)
13	__________	(from calculation)

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TEST

To do problems in this test, students (trainees) need one of the following: slide rule, logarithm table, or calculator with natural logs.

Read each definition in the left hand column. For each definition, write in the blank the letter of the appropriate response found in the right hand column.

1. ____ Any radiated waves consisting of electrostatic and magnetic lines of force.

2. ____ The intensity of radiation is inversely proportional to the square of the distance from the source.

3. ____ The actual number of times an electromagnetic wave recurs per unit time.

4. ____ The physical distance of a complete cycle of a wave.

5. ____ A number expressed in cm^{-1} representing the ability of a material to reduce electromagnetic intensity.

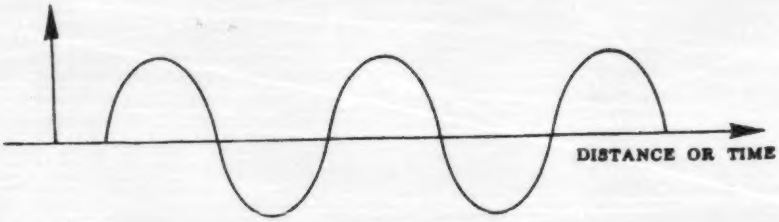
6. ____ A number expressed in $gram/cm^2$ representing the ability of a material to reduce electromagnetic intensity.

a. frequency
b. monobsorption
c. linear absorption coefficient
d. Ohm's Law
e. wavelength
f. mass absorption coefficient
g. electromagnetic radiation
h. intensity
i. x-rays
j. Inverse Square Law

7. List six types of electromagnetic radiation.

a. ______________________________
b. ______________________________
c. ______________________________
d. ______________________________
e. ______________________________
f. ______________________________

8. Given the figure below of the repeating wave pattern, label the wave amplitude and the wavelength.



9. Write the equation that shows the relationship between wave frequency and wavelength.

10. Radiation intensity of a Cobalt-60 source is 120 mR/hr. at three feet from the source. Calculate the intensity at the following distances from the source: four feet, five feet, six feet.

11. If a net count rate of 1000 cpm is reduced to a net count rate of 200 cpm when four inches of concrete are placed between the source and the detector, calculate the following: linear absorption coefficient, mass absorption coefficient, half-value layer. (The density of concrete is 2 grams/cubic centimeter.)

Use Figure 1-6-4 on the next page to answer questions 12, 13 and 14 below.

12. Calculate the fraction of 1 MeV gamma radiation absorbed in lead that is one-half inch thick.

13. Find the energy of a narrow beam, monoenergetic, gamma radiation after passage through 2 centimeters of aluminum whose half-value layer is .77 centimeters.

14. Using Figure 1-6-4 on the next page, locate on the aluminum curve the energy for μ of .9.

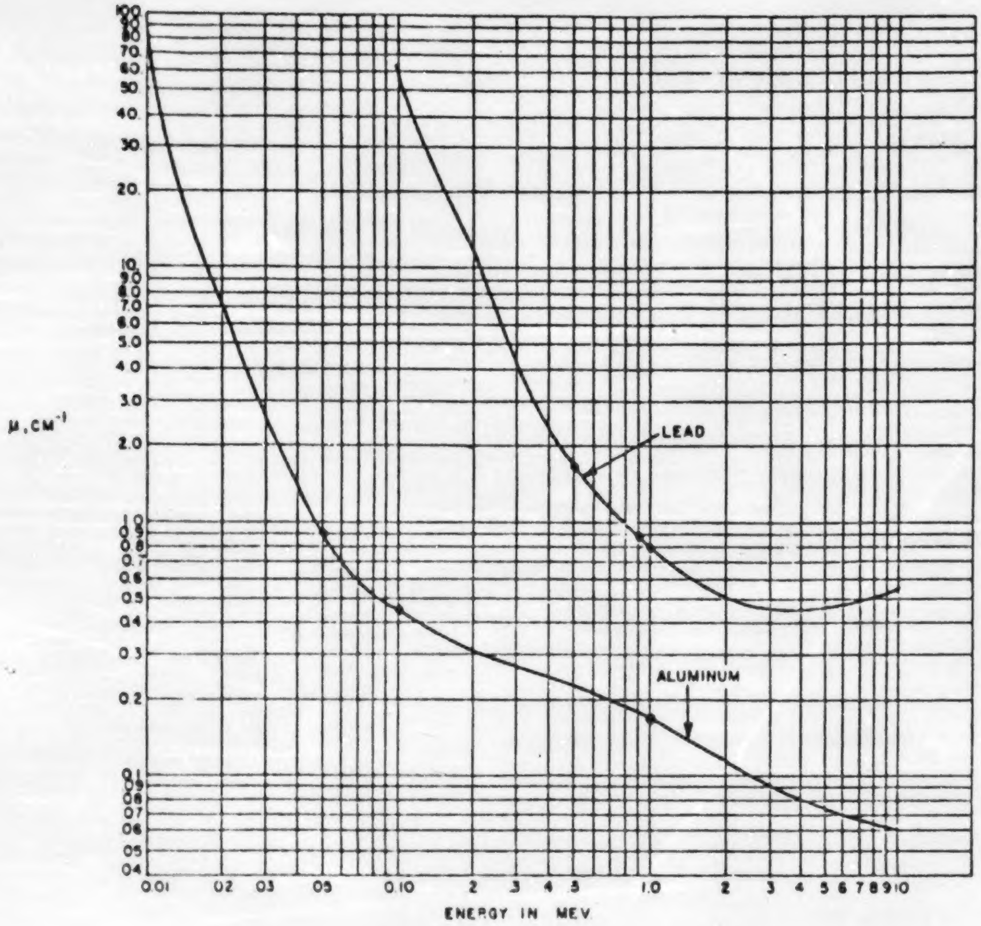


Figure 1-6-4

Linear Absorption Coefficients (μ) for X-Ray and Gamma Radiation in Aluminum and Lead. (From Radiological Health Handbook)

15. Write the equation that shows the relationship between the linear absorption coefficient and the mass absorption coefficient. Very briefly explain the equation that shows the relationship.